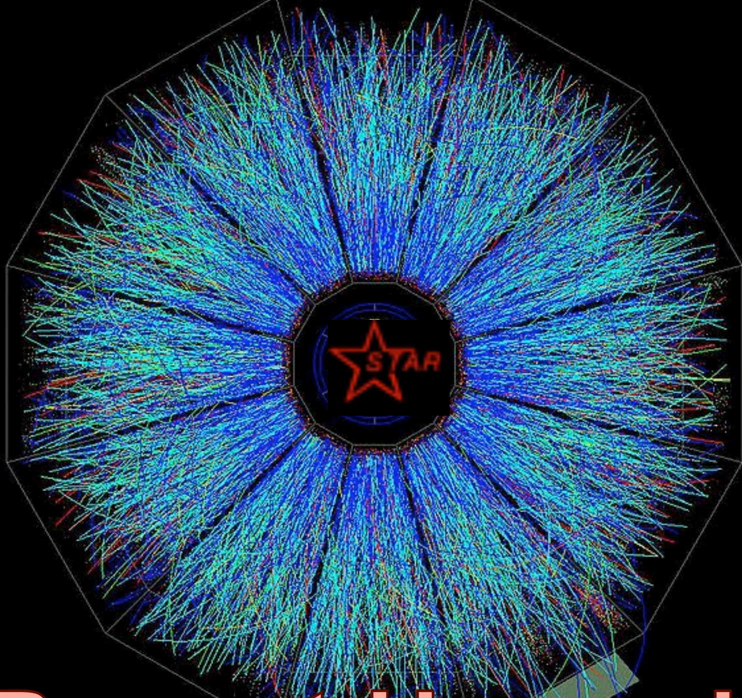
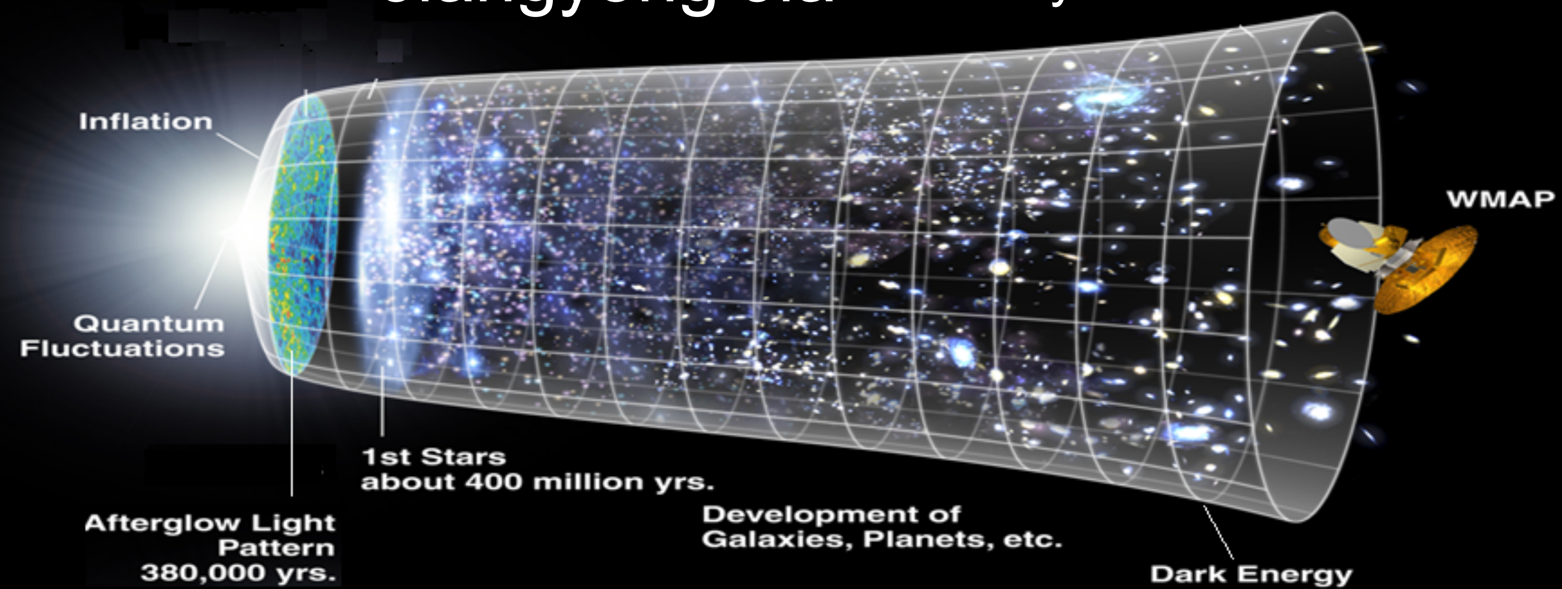


Recent Heavy Ion Results from RHIC

Jiangyong Jia Stony Brook & BNL



Why Heavy ion physics

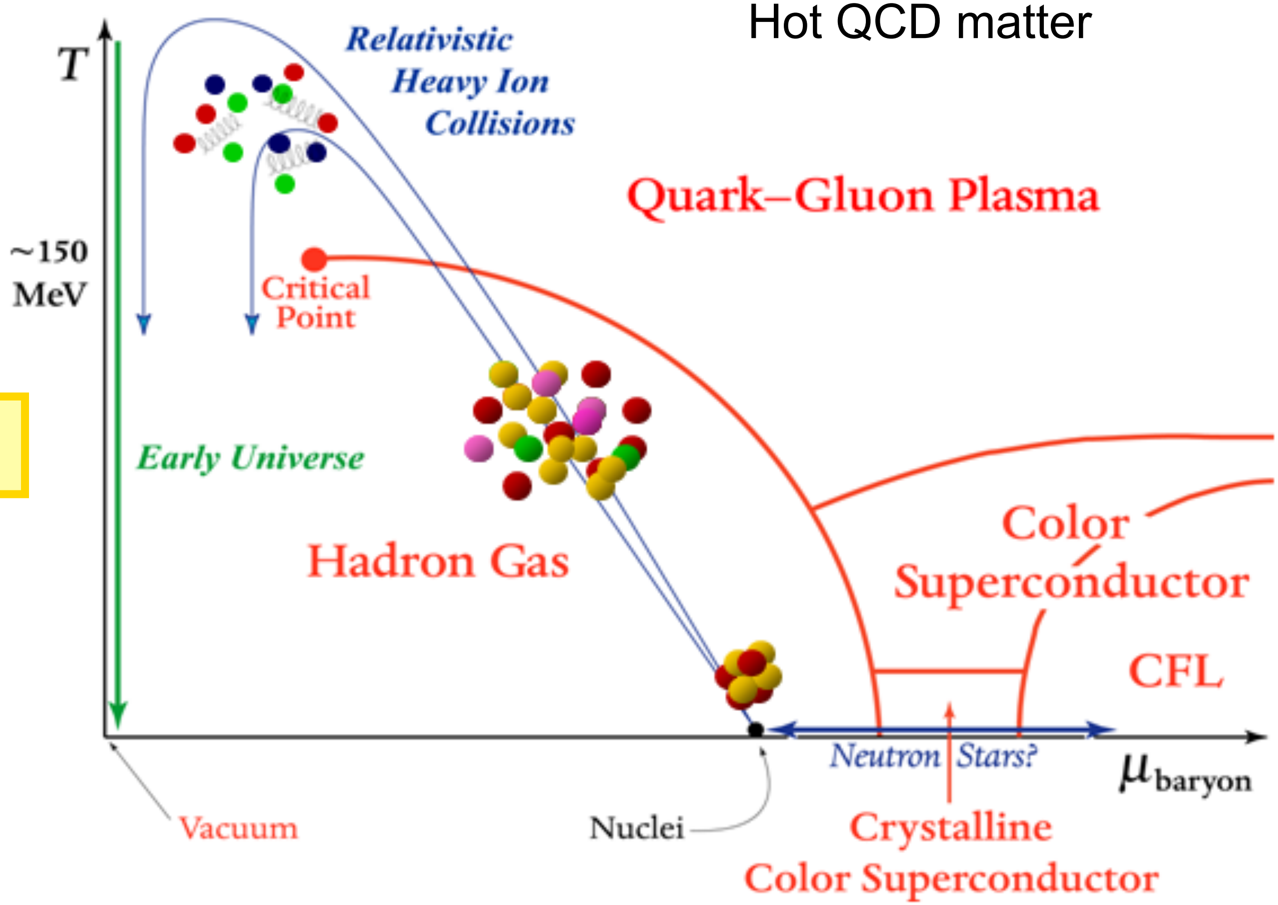
T.D. Lee (1975):

In HEP we have concentrated on…. distribute higher & higher amount of energy into a region with smaller & smaller dimensions.

In order to study the question of "vaccum", we should… distribute higher energy over a relatively large volume.

Hot QCD matter

Nuclear Matter



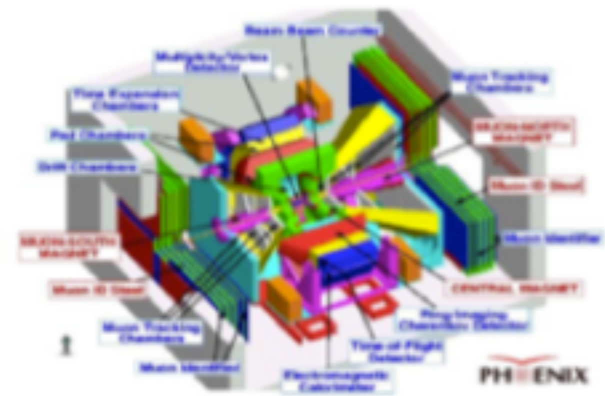
Connection to cosmology

- HI collision is the only way to emulate the condition few microseconds after the big-bang, and study properties of quark gluon matter present as that time.
- Connection to some outstanding questions of cosmology: evolution of early universe, matter/anti-matter asymmetry, strangelets.

Agnes Mocsy, Paul Sorensen arXiv:1008.3381

Relativistic Heavy Ion Collider (RHIC)

- Experiments: PHENIX& STAR

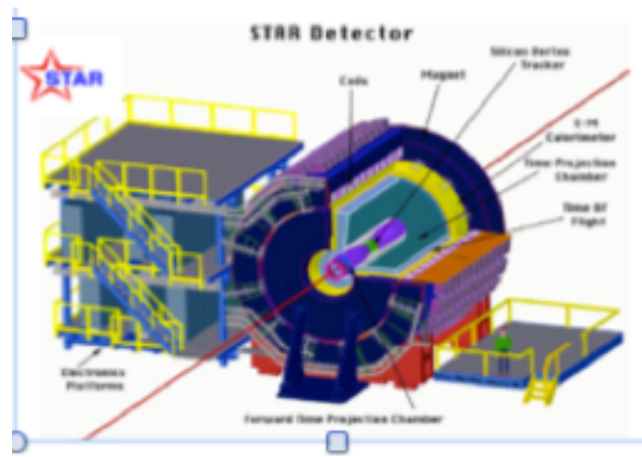


- RUN 2000-2011

Au-Au,Cu-Cu @ $\sqrt{s_{NN}} = 5 - 200$ GeV

U+U next year

Hot QCD, CEP search



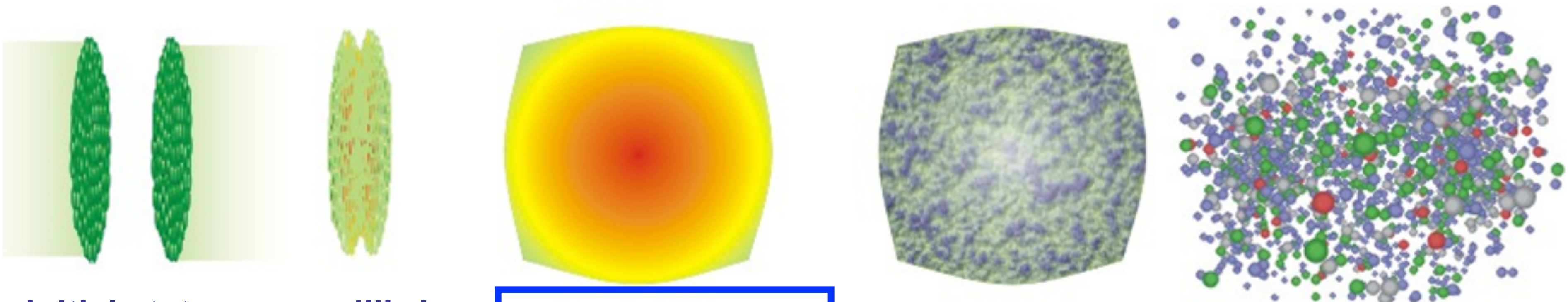
d-Au @ $\sqrt{s_{NN}} = 200$ GeV

Cold QCD: NPDF, Saturation physics.
WG2S1 C. Perkins, J. Lajoie

p-p, p↑-p↑ @ $\sqrt{s} = 22\text{-}500$ GeV

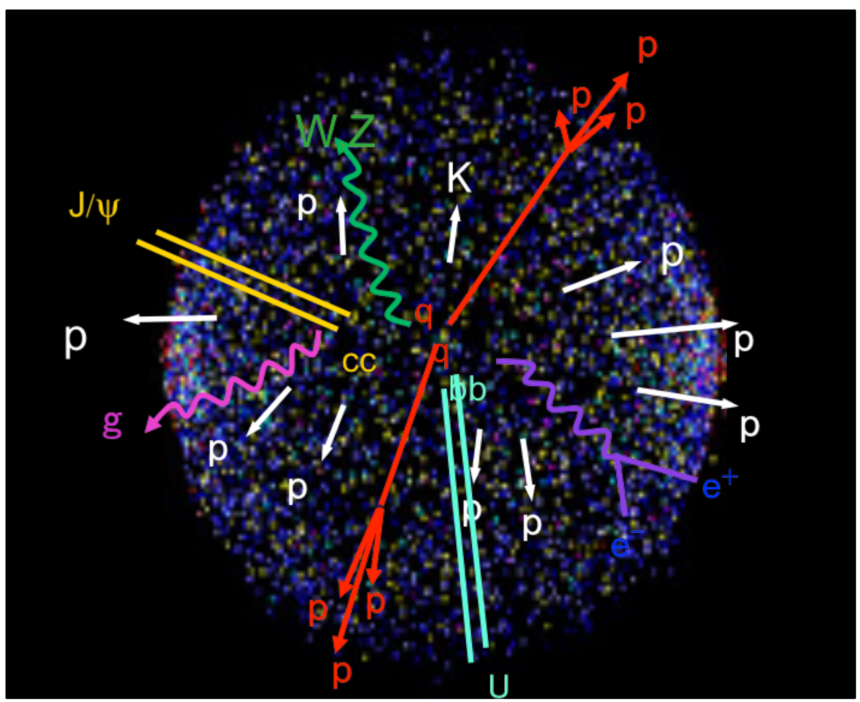
Spin physics, ref for HI

Space-time history of heavy ion collisions

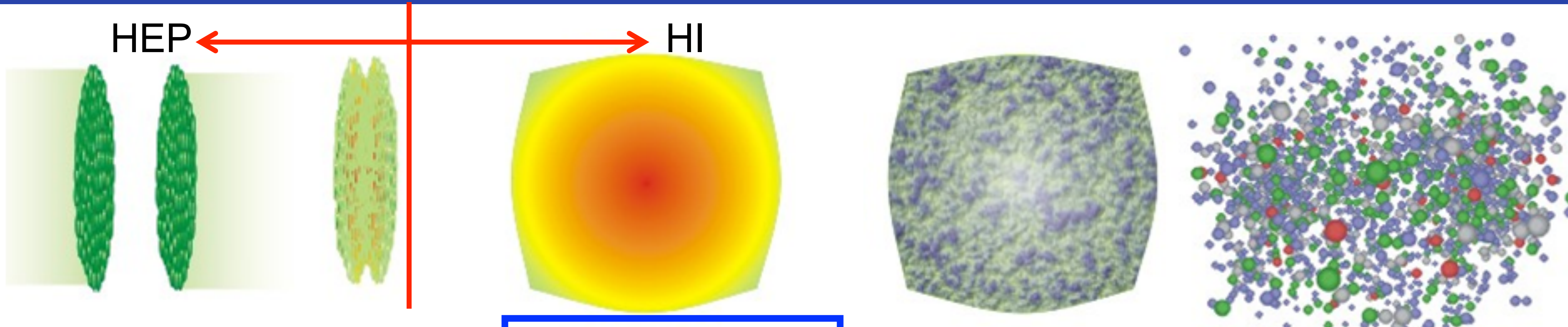


initial state pre-equilibrium **QGP & expansion** Phase transition Freeze-out

400 400→6000 in 10^{-23} second! 6000



Space-time history of heavy ion collisions

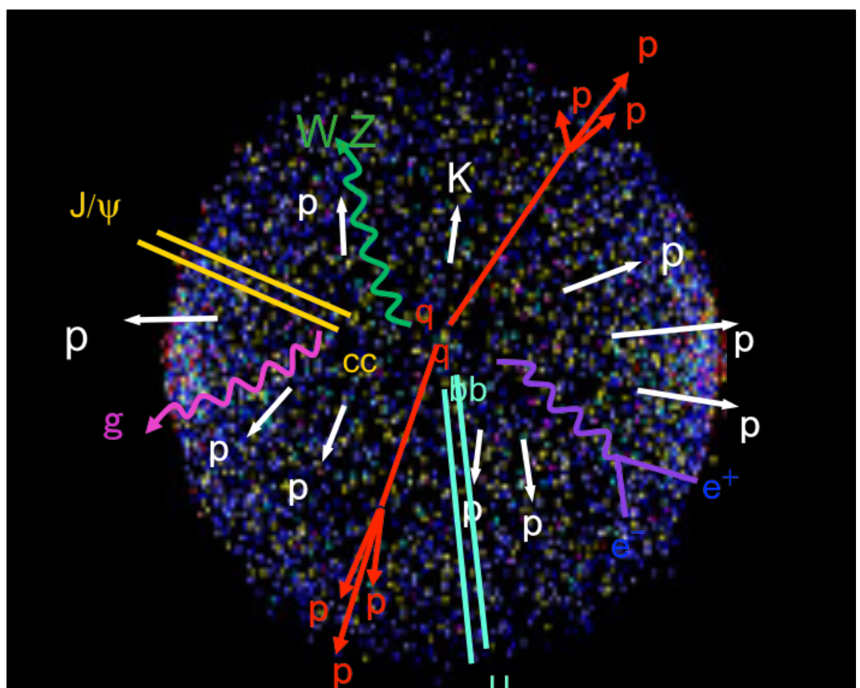


initial state **pre-equilibrium** **QGP & expansion** **Phase transition** **Freeze-out**

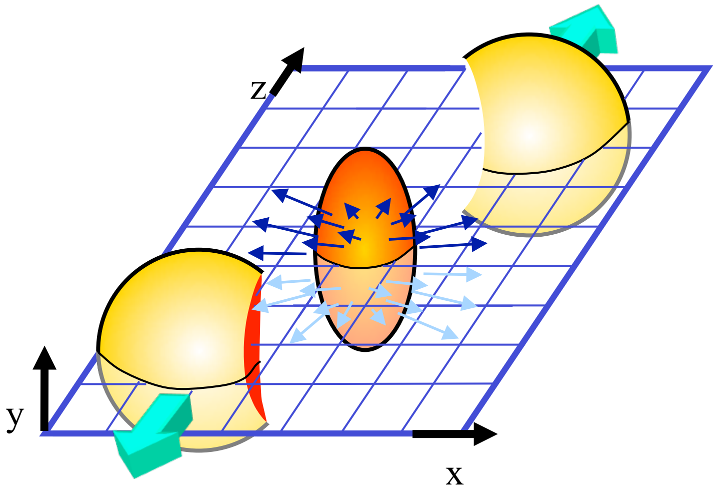
400

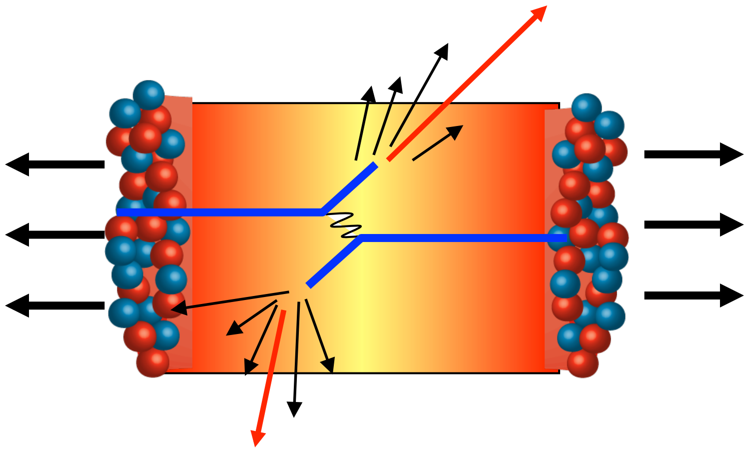
400→6000 in 10^{-23} second!

6000



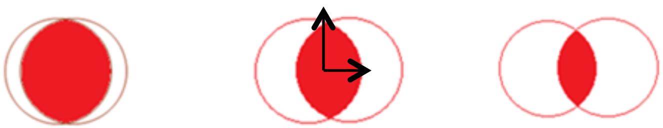
Extracting properties of Quark Gluon Plasma





- How hot/dense is the matter?
- How the bulk matter behave?
- What is the stopping power of the matter?
- How the matter respond to perturbations?

Understand and control the geometry of bulk matter is very important!



Centrality,
Species & energy scan
p+p, p+A references

How hot/dense is the matter?

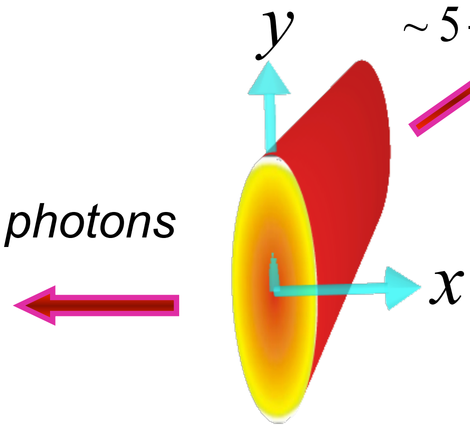
- Energy density estimated from total E_T measurement
- Temperature estimated from thermal γ radiation

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

$$\sim 5-15 \ \frac{GeV}{fm^3}$$

QGP radiates photons

$$\gamma^* \rightarrow e^+ e^-$$



How hot/dense is the matter?

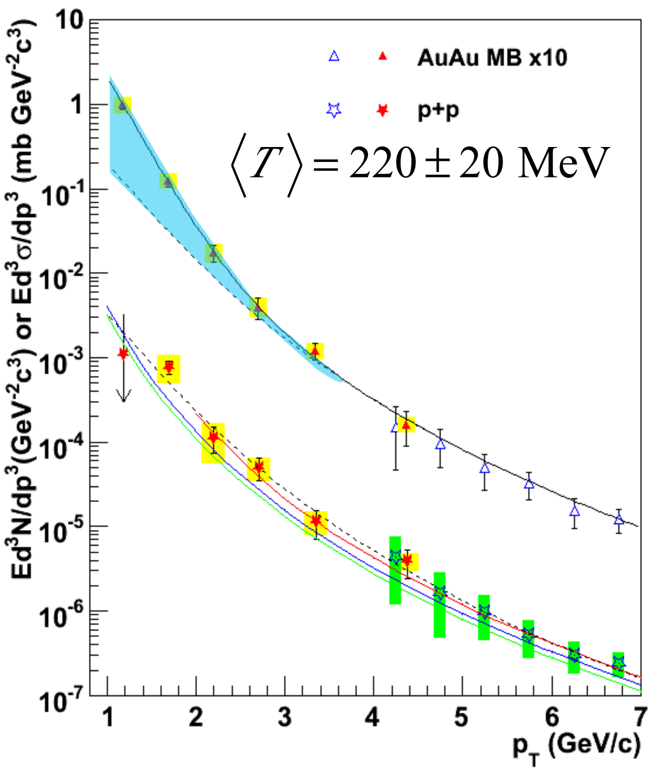
- Energy density estimated from total E_T measurement
- Temperature estimated from thermal γ radiation
  - Thermal component of the spectra <T> =220 MeV
  - Initial temperature from models, 300-600 MeV

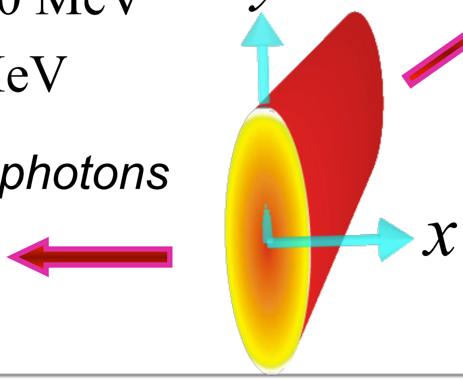
$$\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{\tau_0}\frac{dE_T}{dy}$$

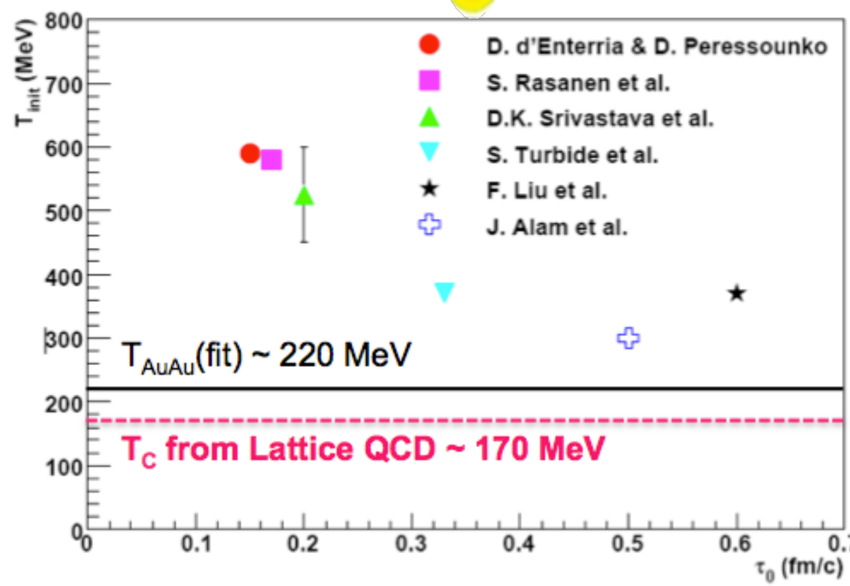
$$\sim 5-15\ \frac{GeV}{fm^3}$$

QGP radiates photons

$$\gamma^* \rightarrow e^+e^-$$

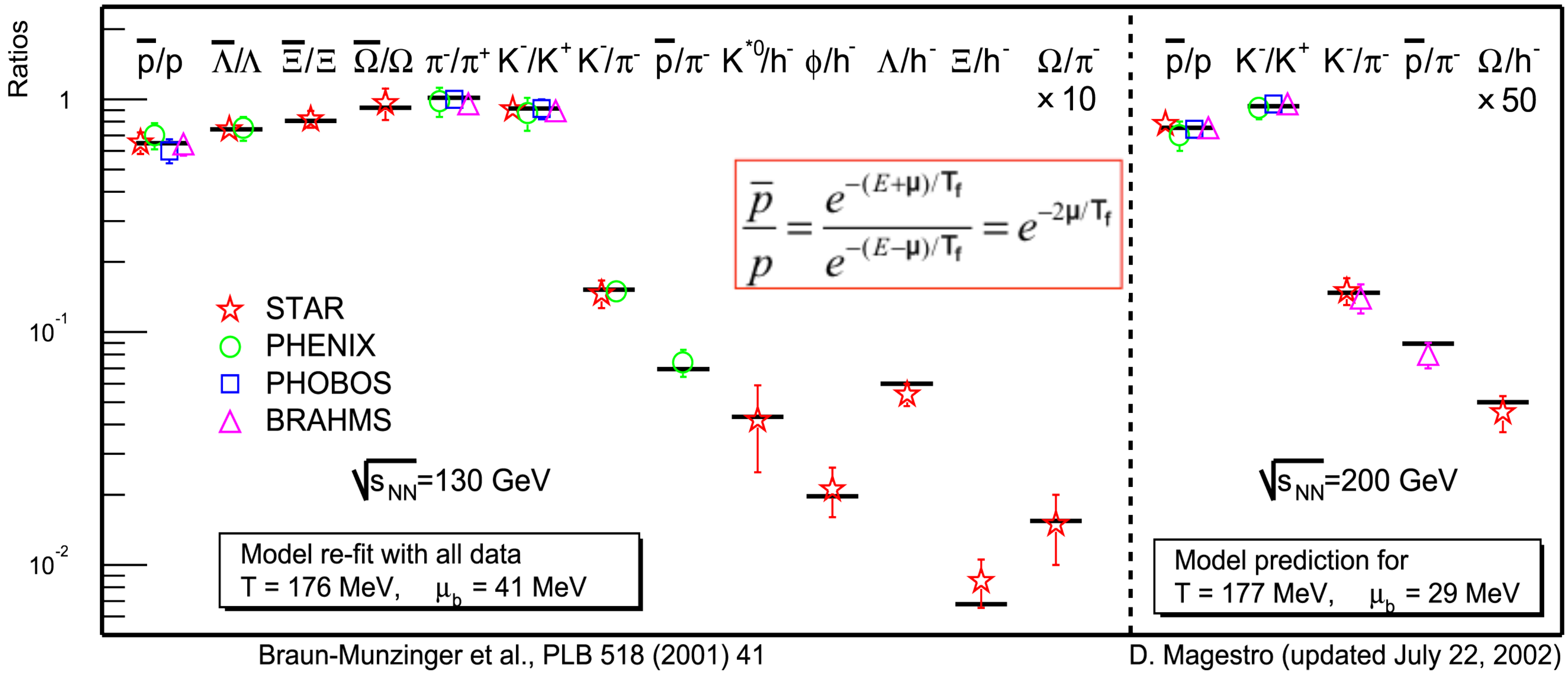






Well above Lattice QCD prediction of a phase transition to quark gluon plasma at T_c ~ 170 MeV and ~1 GeV/fm^3!

Hadron chemistry



- Population of hadron species following statistical distribution

Indicates a single Hadronization
Temperature ~ 175 MeV, μ_B ~ 29 MeV (200 GeV)
Nearly equal amount matter and antimatter!!

RHIC as an antimatter machine

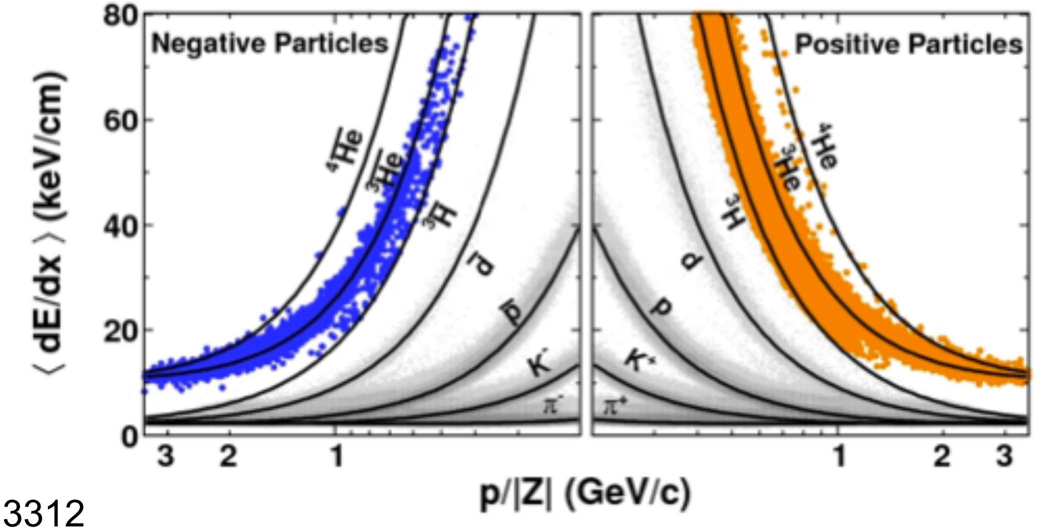
- Heaviest antimatter nucleus observed by STAR
  - Anti-hypertriton in 2010

    $${}^{3}_{\bar{\Lambda}}\overline{H}(\bar{n}+\bar{p}+\bar{\Lambda})$$

    Science **328**, 58 (2010)
  - Anti-helium4 in 2011

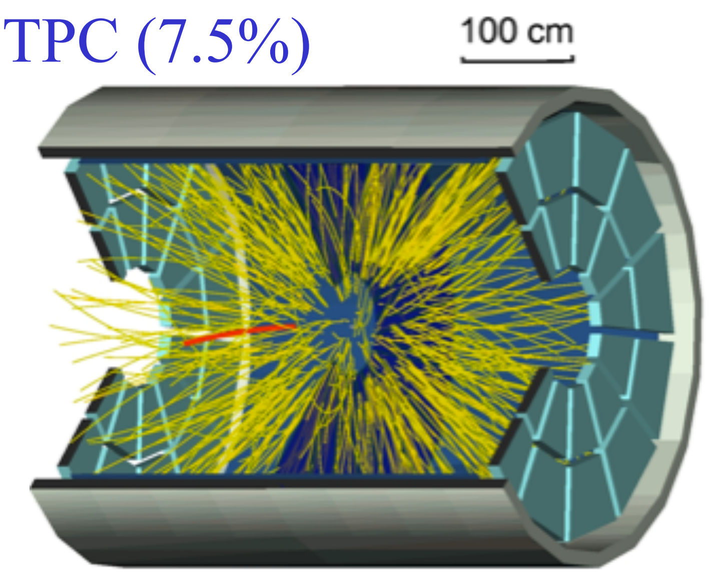
    $${}^{4}\overline{He}(\bar{n}+\bar{n}+\bar{p}+\bar{p})$$

    arXiv:1103.3312
    Submitted to Nature

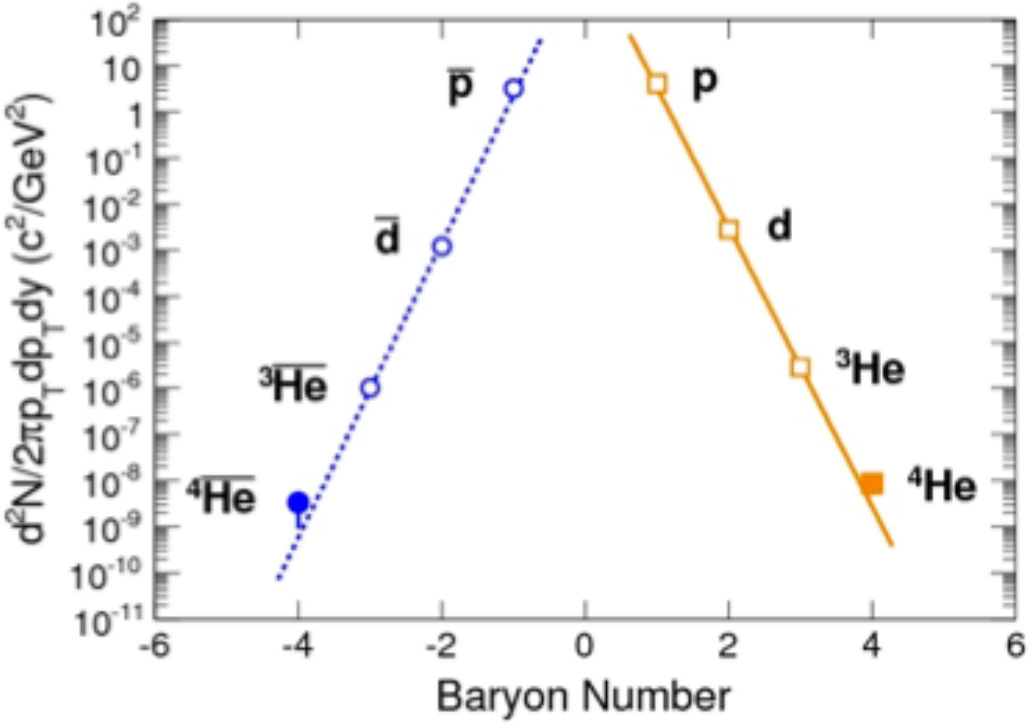


- Identification via TOF (95ps) and dE/dx of TPC (7.5%)

Identfied18 ${}^{4}\overline{He}$ candidates in 10^9 Au+Au events or 0.5 trillion tracks!



RHIC as an antimatter machine

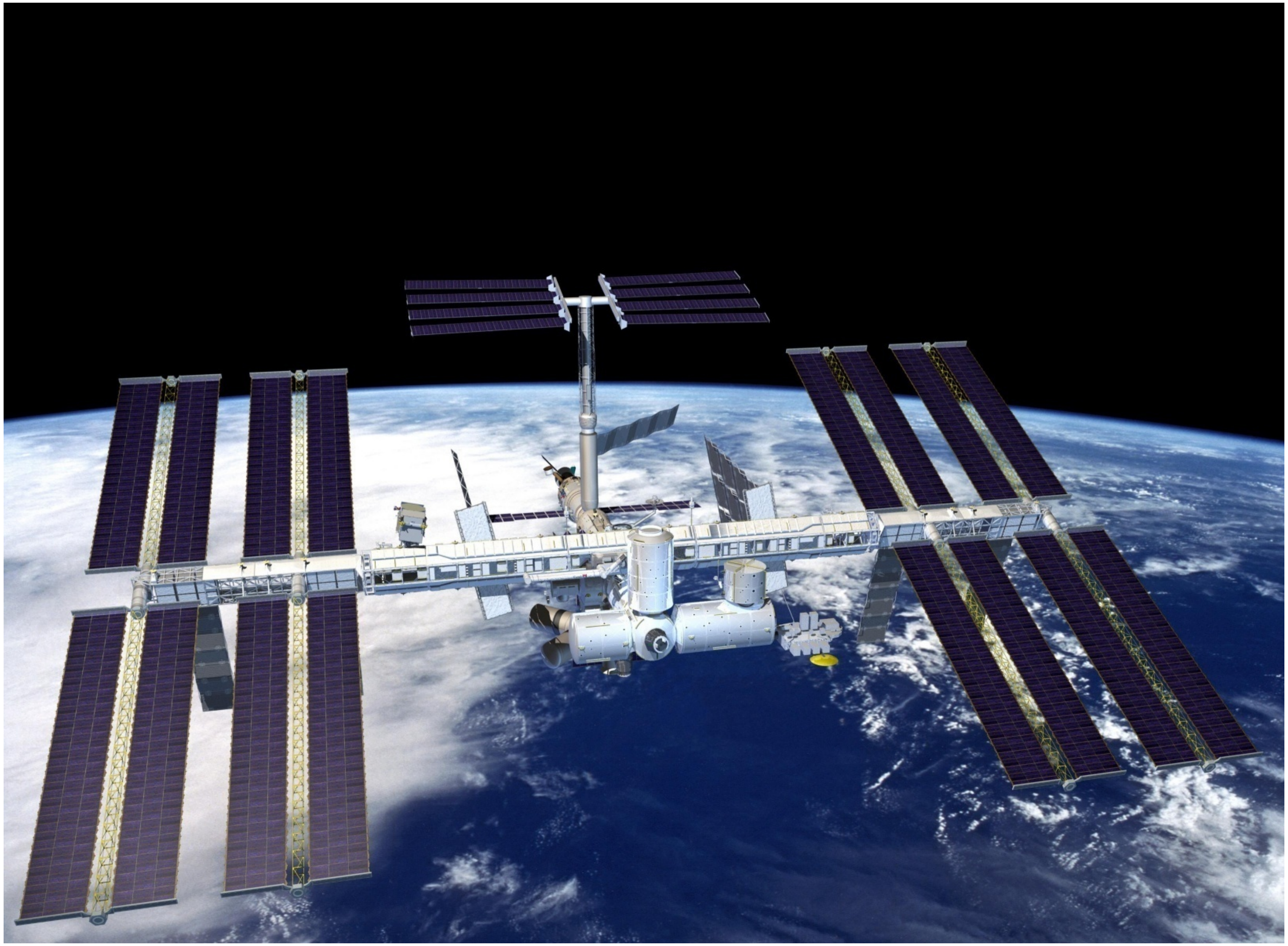


- Rate consistent with coalescent nucleosysthesis models
  - Require dense population of almost equal amount of q and qbar over an extended volume! (12 antiquarks)
- Rate decrease by 10^3 for each nucleon added. Extremely unlikely to generate anti-neuclus in cosmic event except in big-bang!
  - Observe naturally produced $^4\overline{He}$ would indicate a large amount of isolated anti-matter in the Universe

AMS-1 on board the ISS

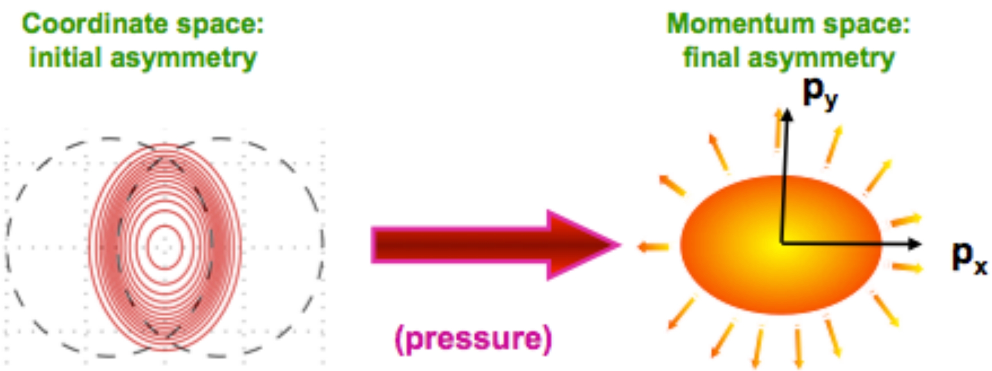
- AMS-2 scheduled: **April 29, 2011 at 3:47 PM**

AMS antiHelium/Helium sensitivity: 10^{-9}

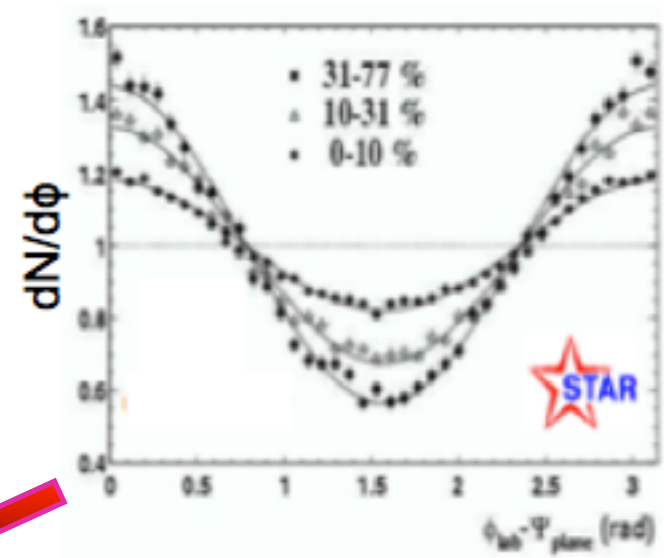


How does the matter behave?

- QGP expands hydrodynamically with low viscosity (small mfp)
- Efficiently transfer asymmetry of initial geometry to azimuthal anisotropy in momentum space



$$\varepsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad V_2 = \frac{\langle p_y^2 - p_x^2 \rangle}{\langle p_y^2 + p_x^2 \rangle}$$



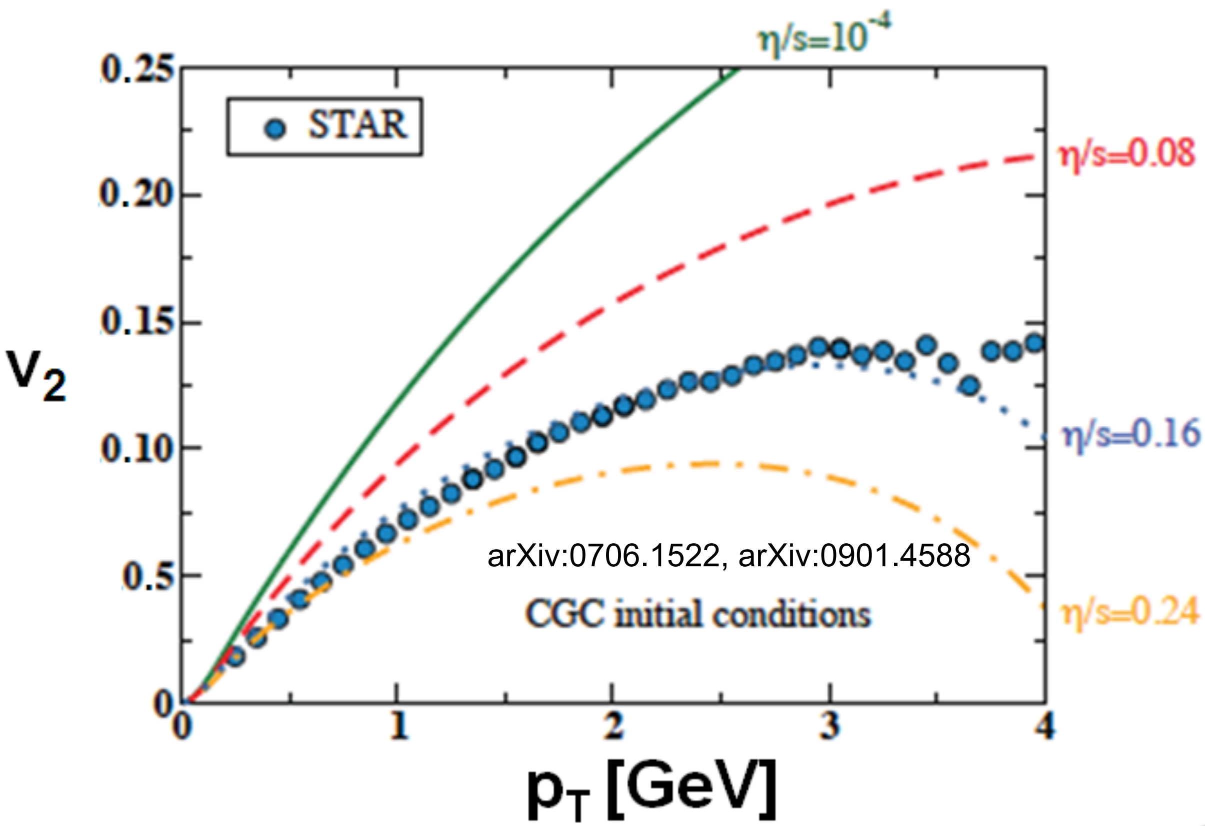
$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos\left[n(\phi-\Psi_{RP,n})\right]\right)$$

Elliptic flow v_2=2[nd] Fourier coefficient

How well the matter flows?

- Modeled by relativistic viscous hydrodynamic
- Stringent constraint on kinematic viscosity $\nu = \frac{\eta}{\rho} \sim \frac{\eta}{s}$ unit is $\frac{\hbar}{k_B}$
- Approaching conjectured quantum lower limit $\frac{\eta}{s} \geq \frac{1}{4\pi} \approx 0.08$
  - Small mean free path, strongly interacting

Kovtun-Starinets-Son, PRL05



$$\frac{\eta}{s} \sim few \times \frac{1}{4\pi}$$

Perfect fluid!

Extensive efforts both experimentally and theoretically to refine

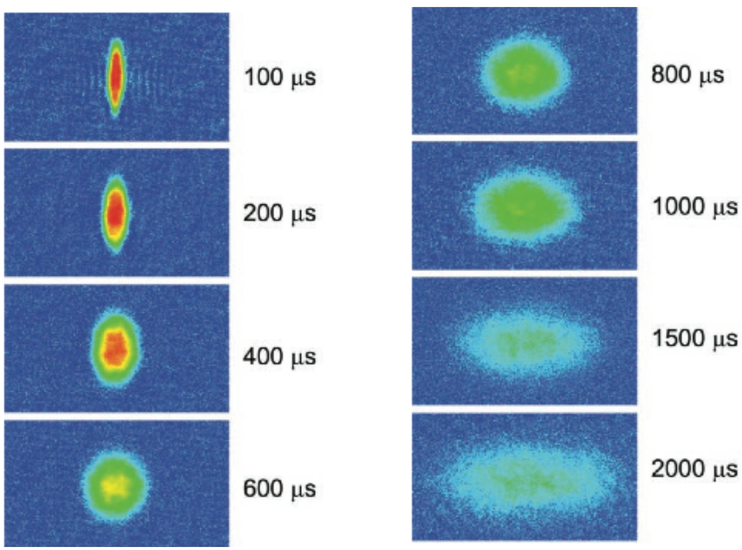
$$\frac{\eta}{s} = 1 - 2.5 \times \frac{1}{4\pi}\frac{\hbar}{k_B}$$

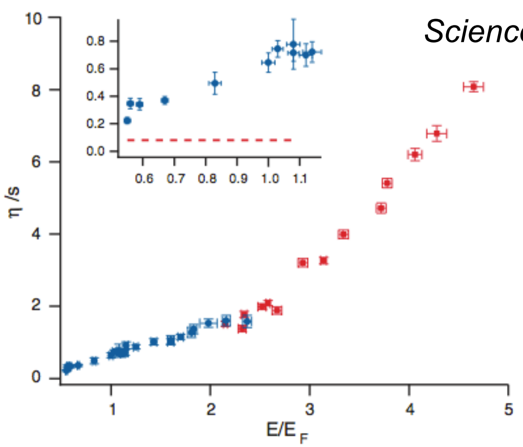
H Song, arXiv:1101.4638

Other strong coupled/interacting system

Universal behavior of strongly interacting medium independent of the force involved!!

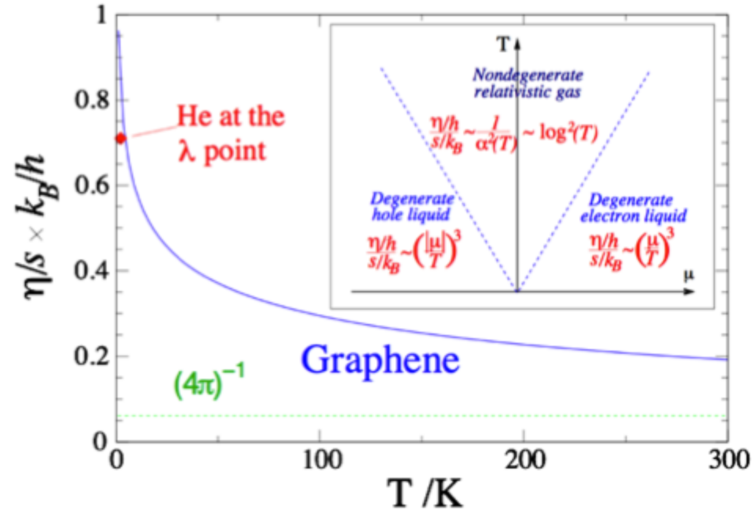
Strongly coupled cold Fermionic atoms in a cigar trap exhibit anisotropy flow Science **298** 2179





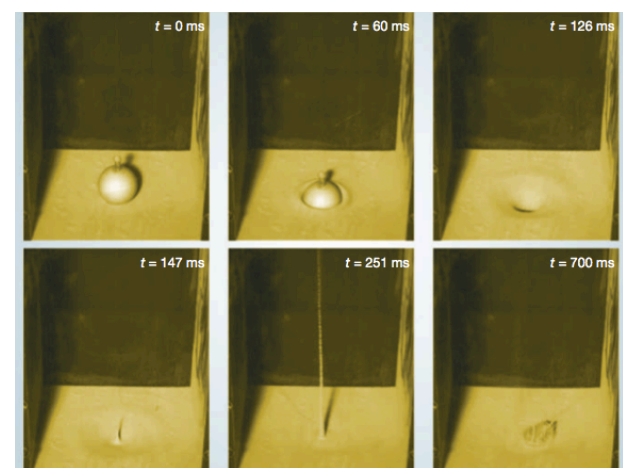
Science **331**, 58 (2011)

Strongly interacting electrons in Graphene PRL 103, 025301

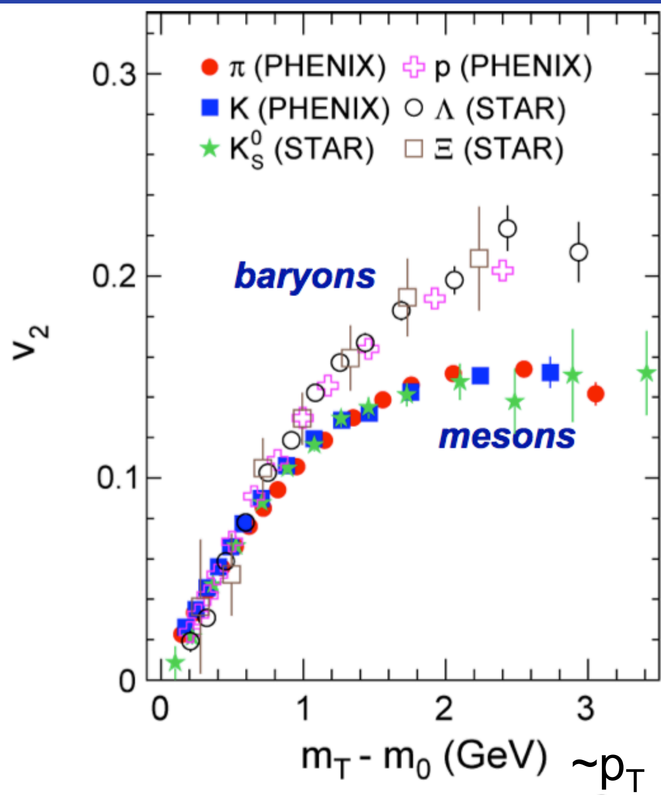


Ball drop in dense granular sands

Nature **432**, 689



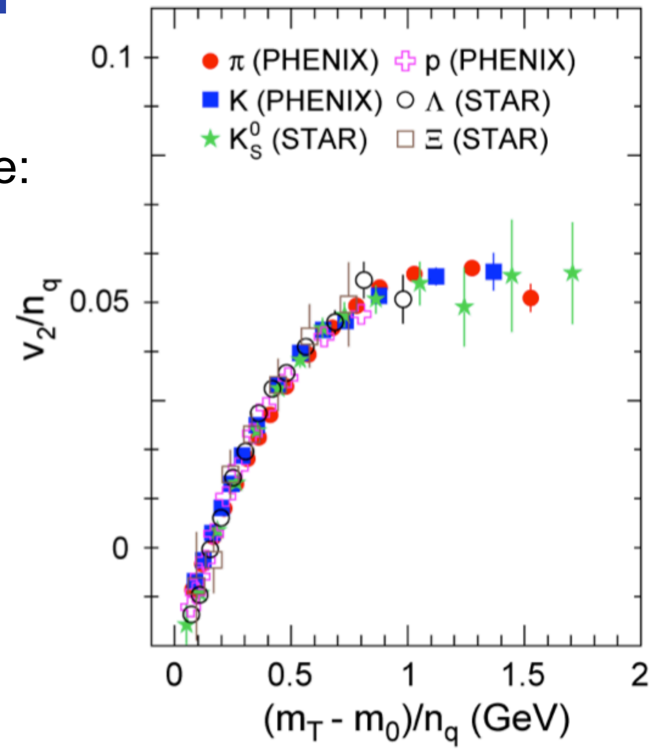
Flow of identified hadrons

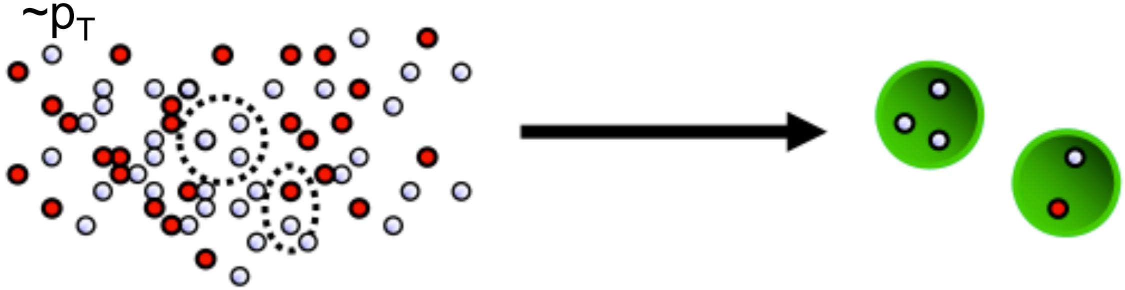


Simple coalescence picture:

Baryon: $v_2(p_T)=3v_{2,q}(p_T/3)$

Meson: $v_2(p_T)=2v_{2,q}(p_T/2)$



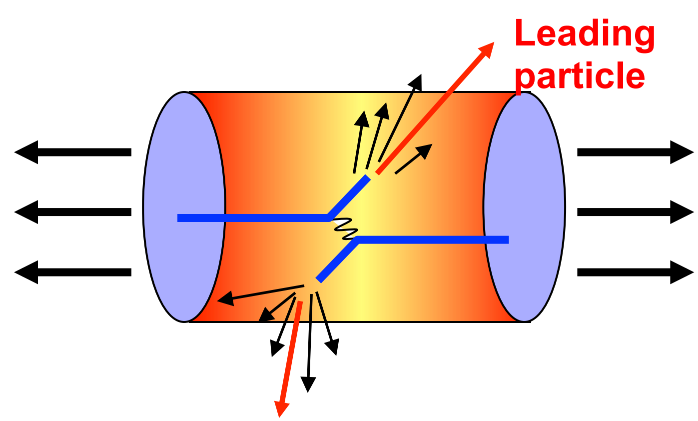


- Hadron flow behave like sum of flow of constituent quarks
  - Flow develop at partonic stage
  - QGP hadronize via quark coalescence

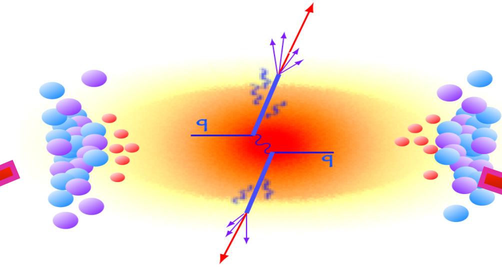
What is the stopping power of the matter?

$$R = \frac{N_2}{N_1} = e^{-kl}$$

- Hard-scattered quarks or gluons (jets) as probe
  - q+q→q+q or g+g
- Single hadron/jet yield $R_{AA} = \frac{\text{Yield}_{AA}}{\langle N_{binary} \rangle_{AA} \text{Yield}_{pp}}$
- Coincidence rate of away-side jet
  - Angular correlations of di-hadron or di-jets

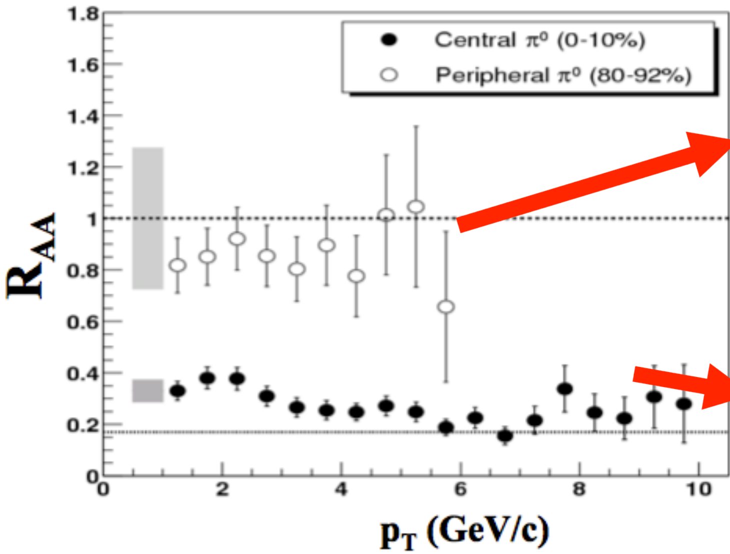


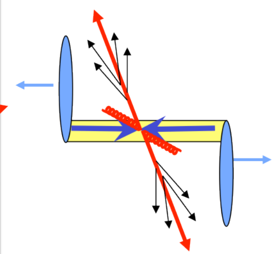
Discovery of Jet quenching

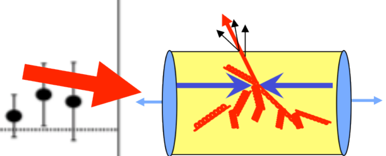


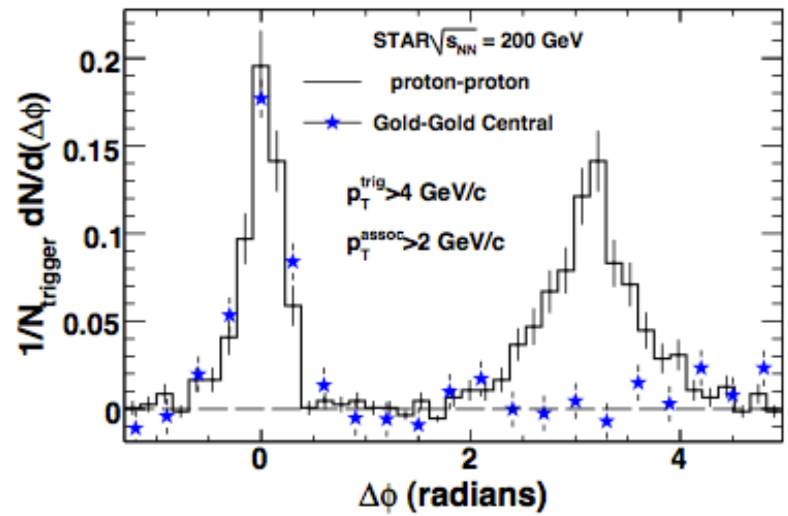
Leading hadron yield

High p_T correlation

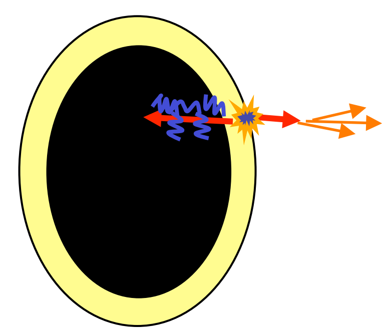






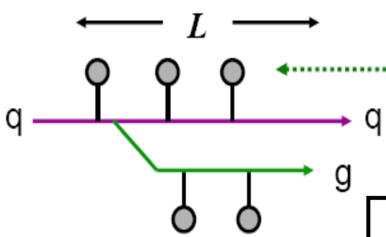


- **In Au+Au collisions we mostly see one "jet" at a time! Surface emission**



Jet quenching as probe of medium properties

Interpretation



Radiative:

$$\frac{dE}{dx} \sim \sigma\rho\left\langle k_T^2 \right\rangle L$$

Color charge scattering centers

Range of Color Force

$$\hat{q} \sim \rho\sigma\left\langle k_T^2 \right\rangle$$

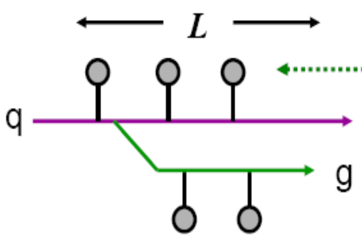
Obtain
ρ and $\hat{q}$

Scattering Power Of Medium

Density of Scattering centers

Jet quenching as probe of medium properties

Interpretation



Radiative:

$$\frac{dE}{dx} \sim \sigma\rho\left\langle k_T^2 \right\rangle L$$

Color charge scattering centers

Range of Color Force

$$\hat{q} \sim \rho\sigma\left\langle k_T^2 \right\rangle$$

Obtain ρ and $\hat{q}$

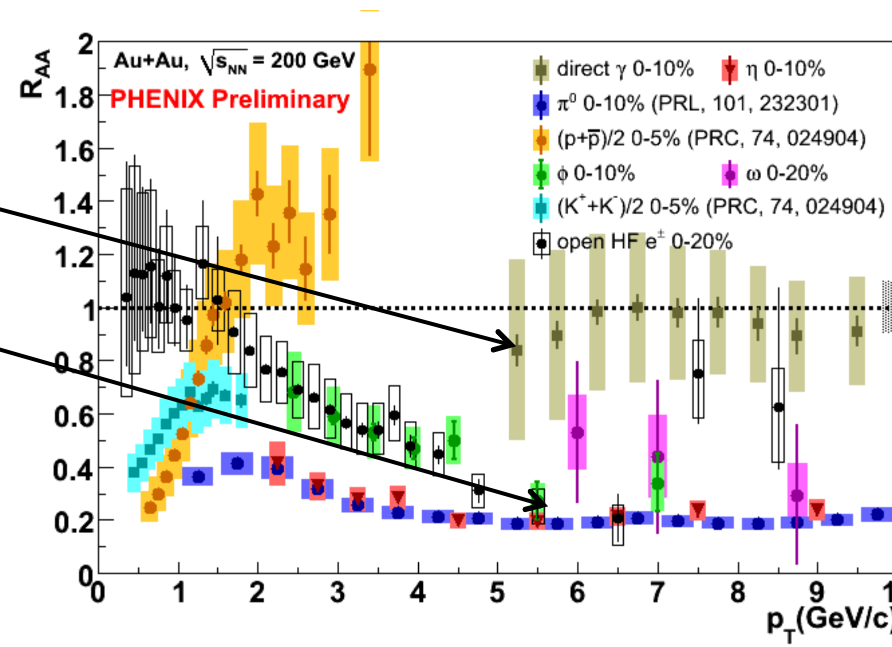
Scattering Power Of Medium

Density of Scattering centers

- Extensive measurements for many probes with different medium coupling.
  - Direct γ, no suppression expected γ
  - heavy quarks D, B, surprisingly strong suppression!! $e^{\pm}$ from D,B
- Constrain medium properties
  - suggest medium is opaque and strongly interacting

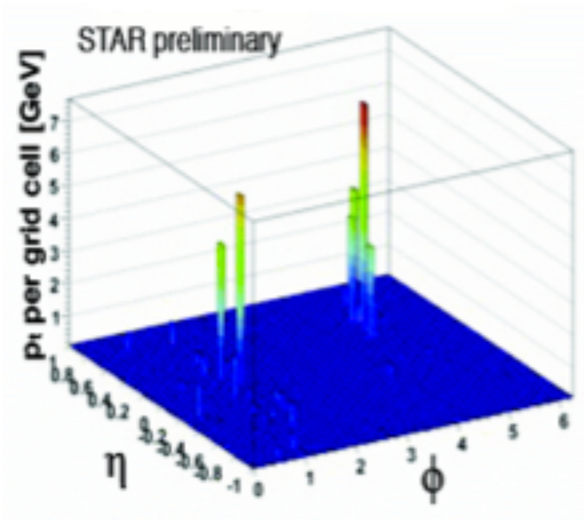
S. Bass et al. arXiv:0808.0908

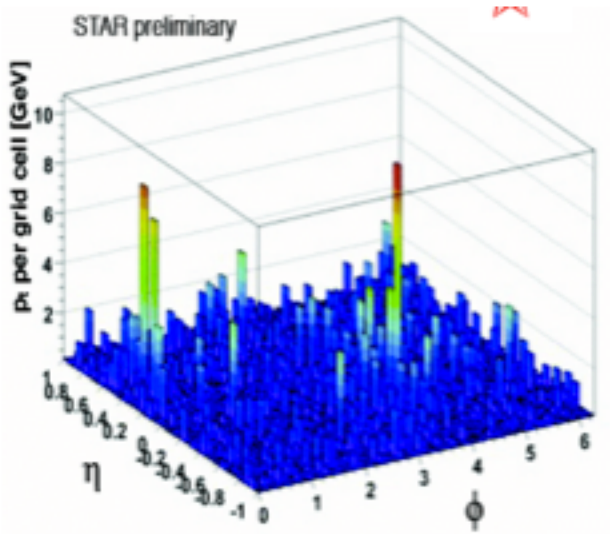
$\langle\hat{q}\rangle$=4-13 GeV²/fm
dN^g/dy~1400±200



Full reco-jet as a probe

- Directly probe jet modifications (energy, shape and FF)
- Challenging due to large & fluctuating underlying event



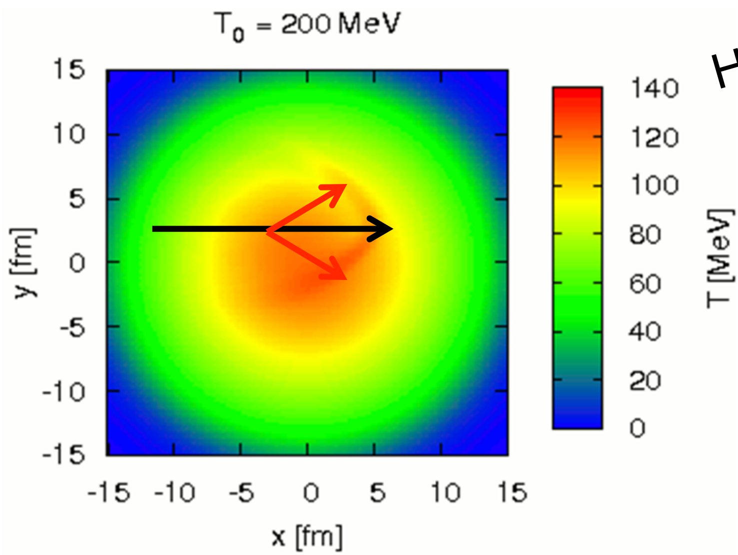


- Complimentary to LHC: large luminosity at RHIC allow access to large x (x~0.5) quark jets (less quenched than gluon jet); also cleaner γ-jet

Extensive efforts on full jet reco, di-jet and γ-jet correlation underway
WG4S1 A. Hanks, J. Rojo, H. Pei, WG4S3 M. Connors

Reaction of the Perfect fluid?

- The lost energy has to go somewhere… shock wave in nuclear matter?

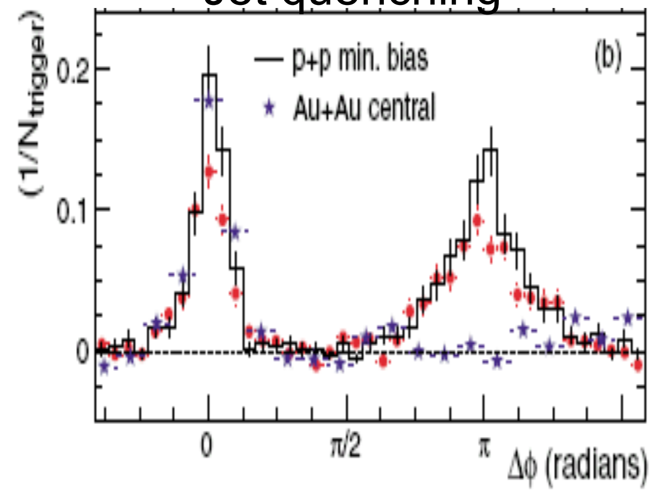


Viscous hydro simulation

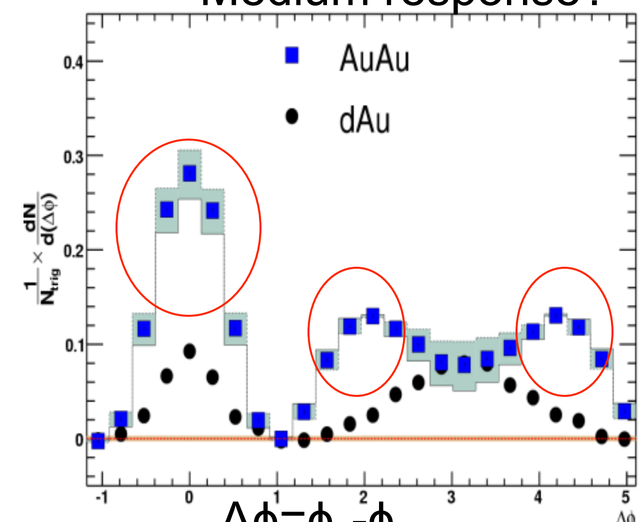
High p_T correlation

Low p_T correlation

Jet quenching



Medium response?

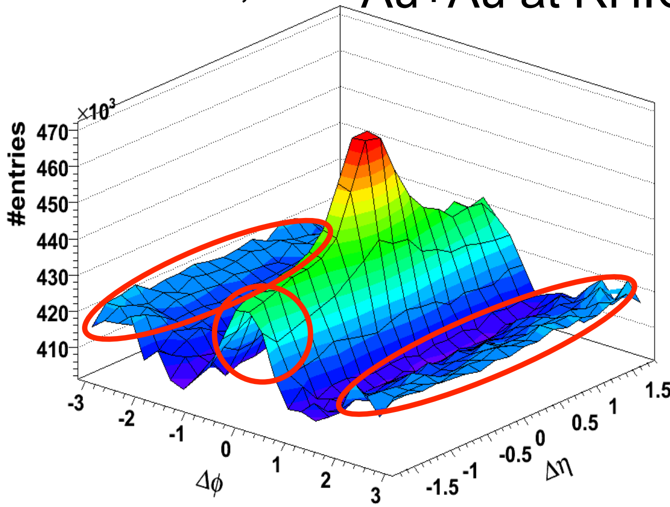


$\Delta\phi = \phi_a - \phi_b$

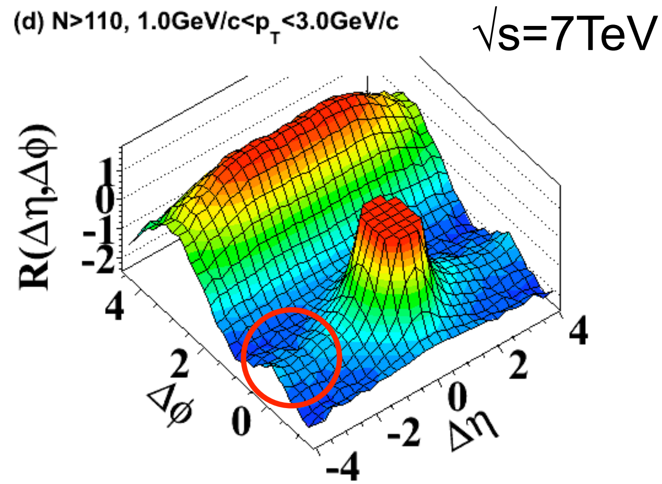
Many calculations suggest that in principle it should exist, but likely to be washed out at the end: viscosity, freezeout, wake contribution

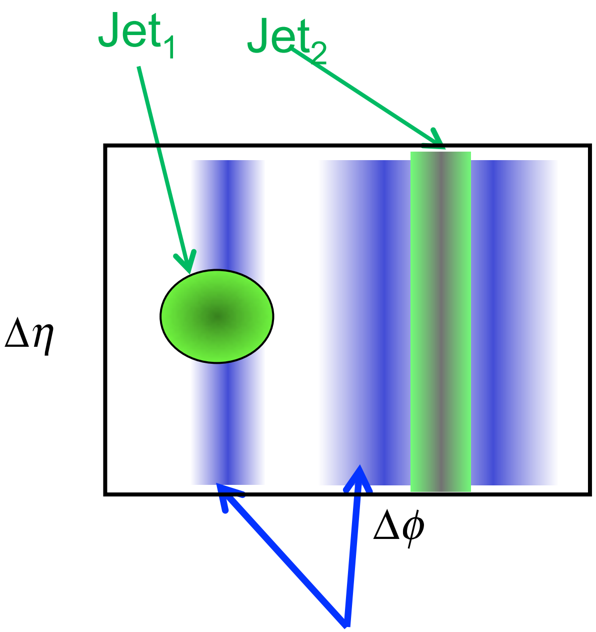
What is this extra stuff in di-hadron correlation?

Phys.Rev.C80:064912,2009 Au+Au at RHIC



CMS p+p (N>110)





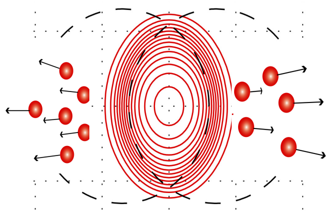
Long range Δη structure seen on both near- and away-side, also in near-side high mul. p+p up to Δη=4

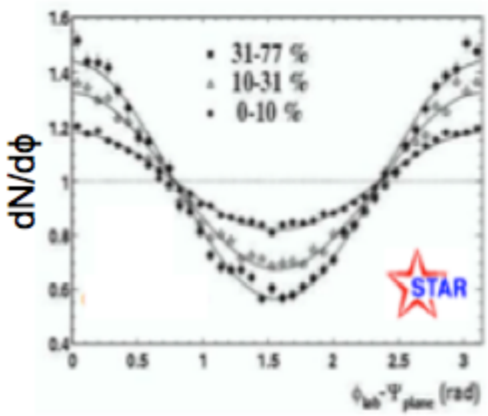
- ❑ Near side : ridge
- ❑ Away side: double hump, double shoulder

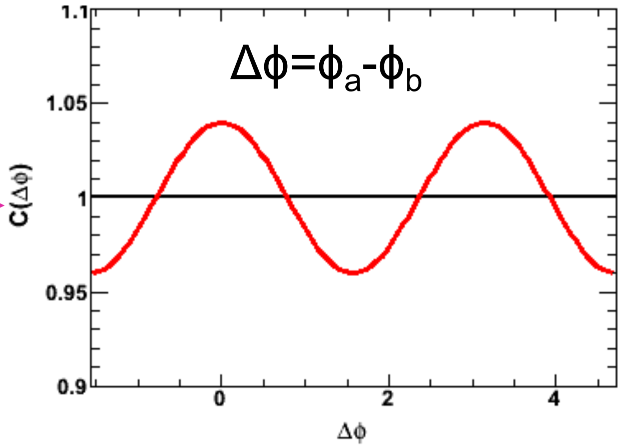
Causality argument seems to rule out transport of jet modifications into large Δη

Flow or jet in-medium response?

Initial geometry and elliptic flow correlation







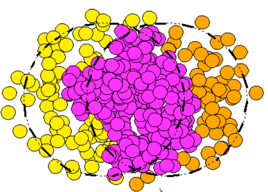
$$\frac{dN}{d\phi} \propto 1 + 2V_2 \cos 2(\phi - \Psi_{RP,2})$$

$$\frac{dN}{d\Delta\phi} \propto 1 + 2V_2^a V_2^b \cos(2\Delta\phi)$$

- Global correlations with initial geometry lead to self-correlations among particles.
- Has been subtracted in two particle correlation already.

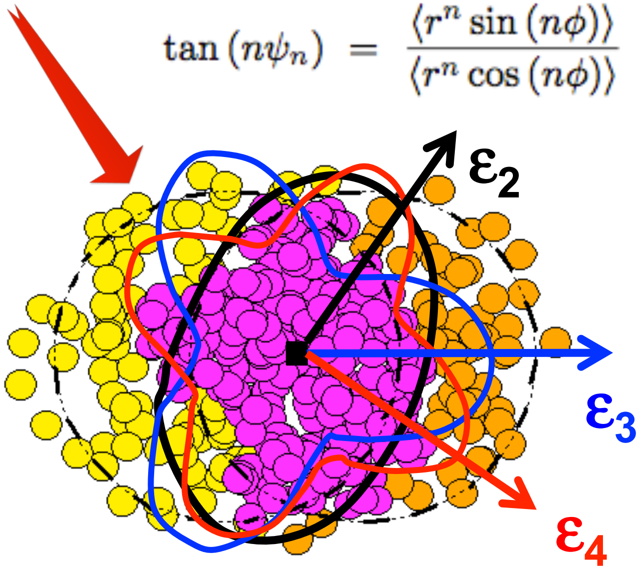
Higher order harmonic flow?

- Initial density fluctuations of nucleons, leads to higher moments of deformations, each has its own orientation.



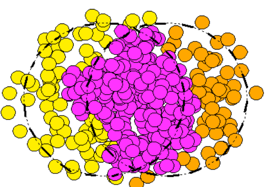
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$\tan(n\psi_n) = \frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$



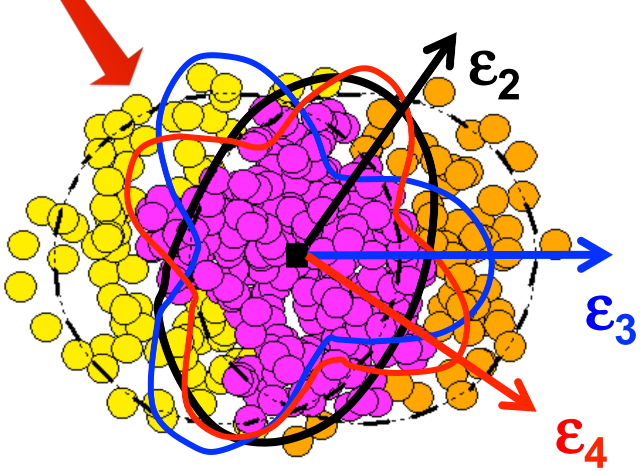
Higher order harmonic flow?

- Initial density fluctuations of nucleons, leads to higher moments of deformations, each has its own orientation.
- They are transferred to p_T space, thanks the low viscosity of sQGP
  - Each space term gives one anisotropy term: $\varepsilon_n \rightarrow v_n$ and $\psi_n = \Psi_{RP,n}$.
  - In 2-p correlation, pairs appear as narrow peak at near-side (all moments in phase), a broad peak at away-side (out of phase)



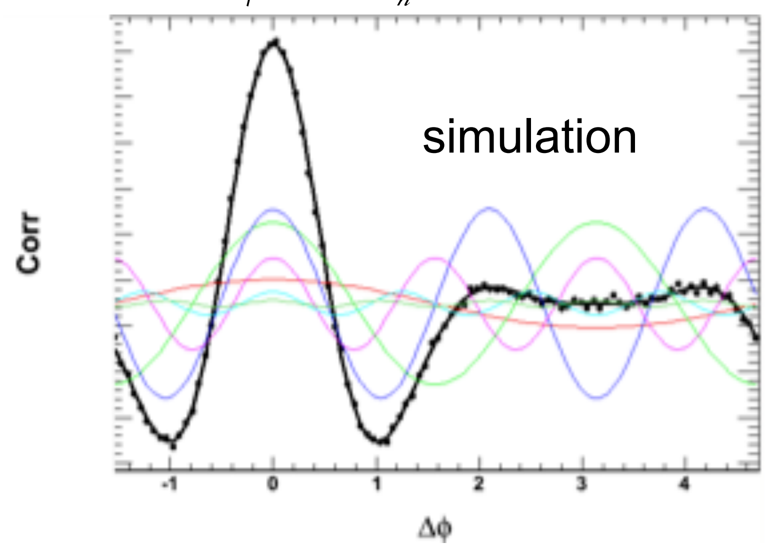
$$\epsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

$$\tan(n\psi_n) = \frac{\langle r^n \sin(n\phi)\rangle}{\langle r^n \cos(n\phi)\rangle}$$



Singles: $$\frac{dN}{d\phi} \propto 1 + \sum_n 2V_n \cos n\left(\phi - \Psi_{RP,n}\right)$$

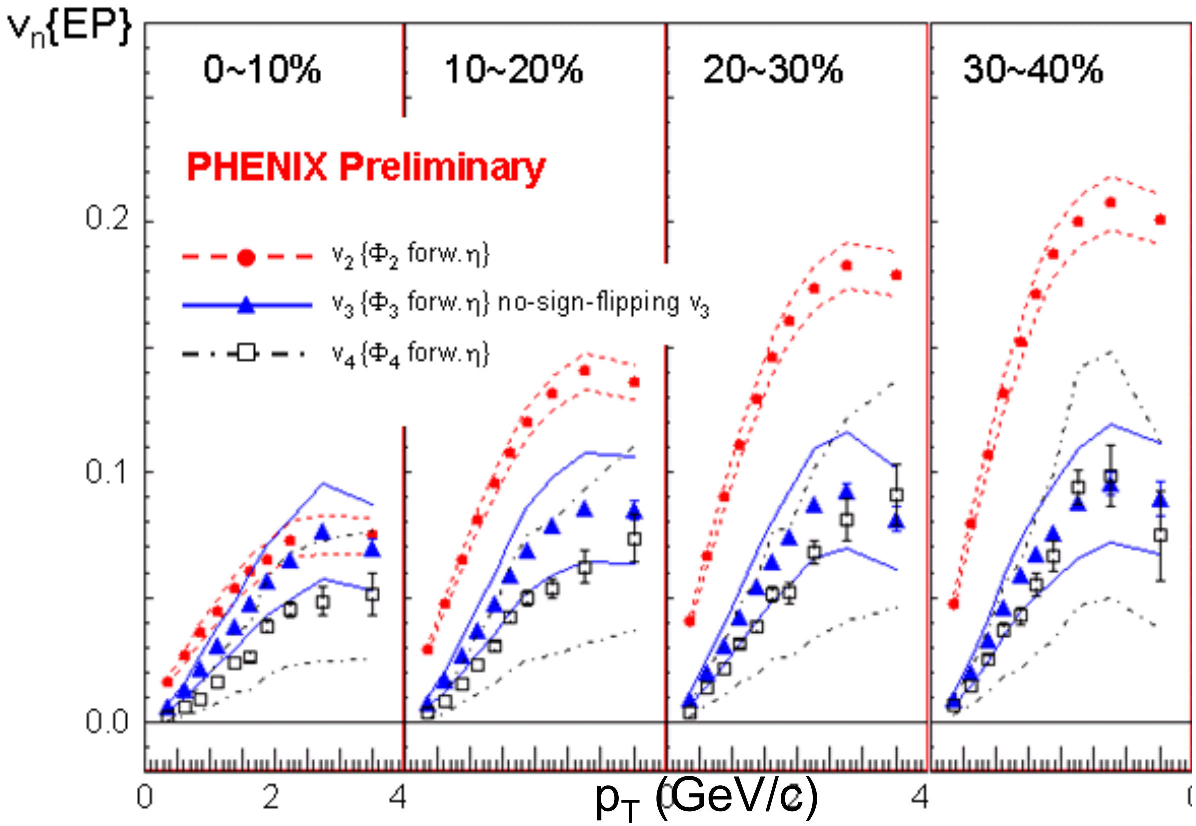
Pairs: $$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2V_n^a V_n^b \cos\left(n\Delta\phi\right)$$

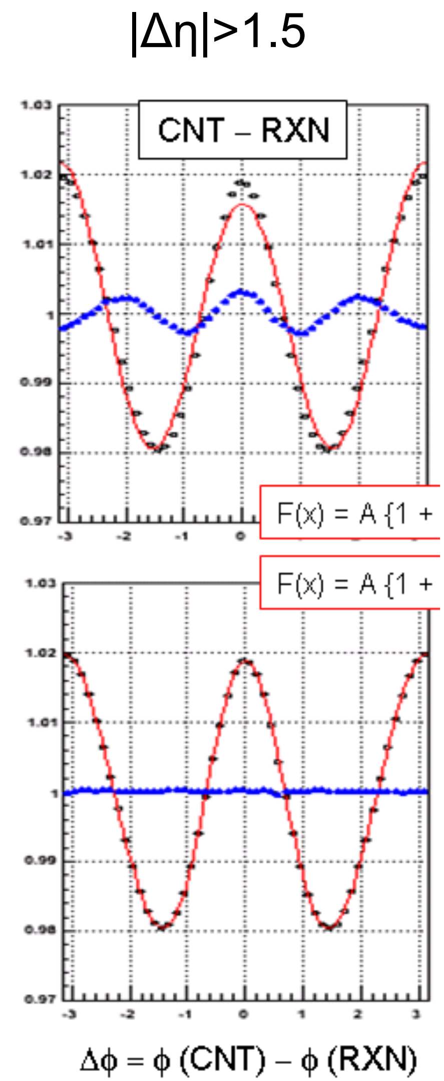


Since flow is a global event characteristics, the correlation should be extended in Δη.

Measurement of higher order harmonics

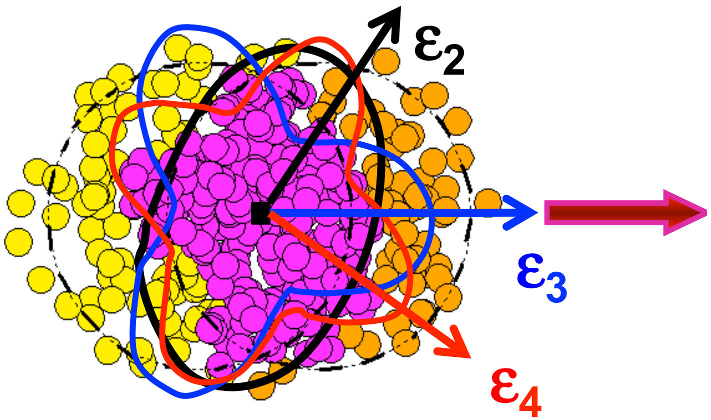
- First measurement of v_3 and v_4 from PHENIX
- Two particle correlation exhausted by v_1-v_4!





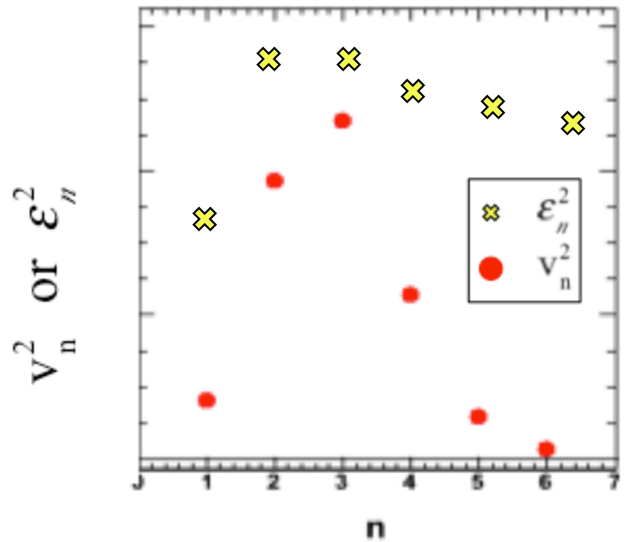
Remember v_n is the power spectrum in angle space

Probing the initial geometry fluctuation



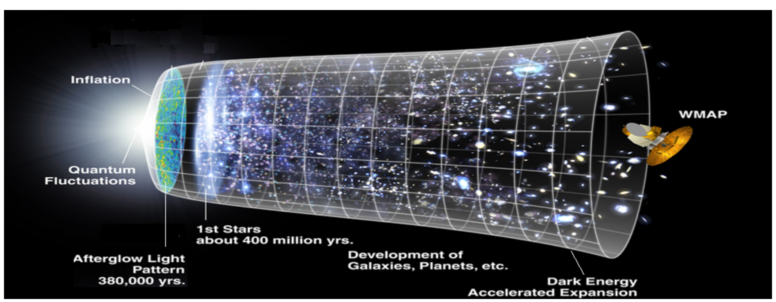
For Illustration only

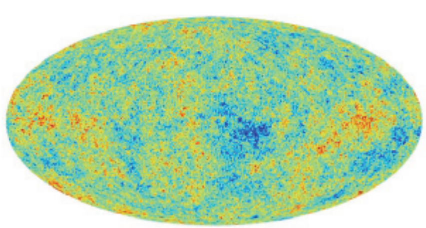
$$f(\Delta\phi) = A(1 + 2V_1^2\cos(\Delta\phi) + 2V_2^2\cos(2\Delta\phi)$$



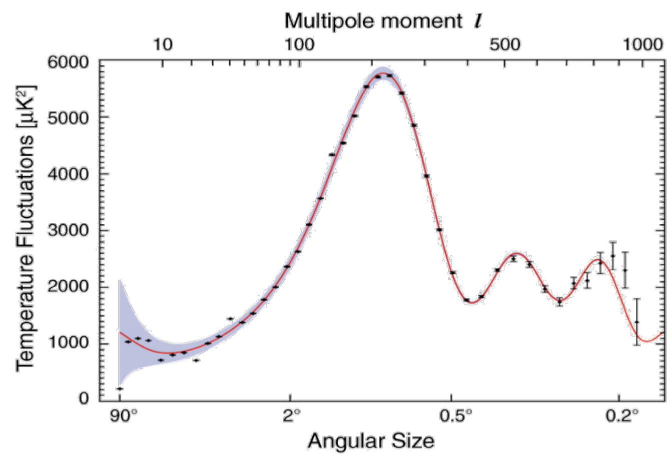
- ❑ Constrain η/s
- ❑ Constrain shape of initial geometry!

P. Sorensen arxiv1102.1403





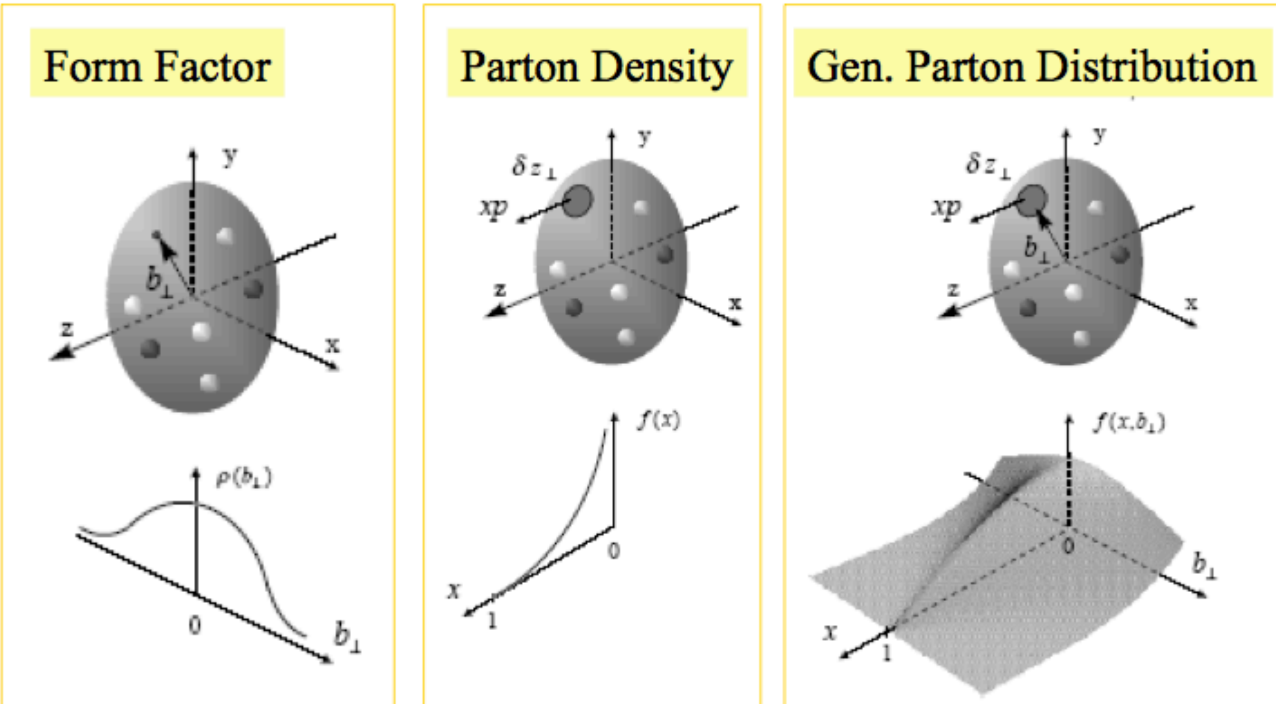
CMB temperature map: fluctuations ~10^{-5}



Stay tuned!

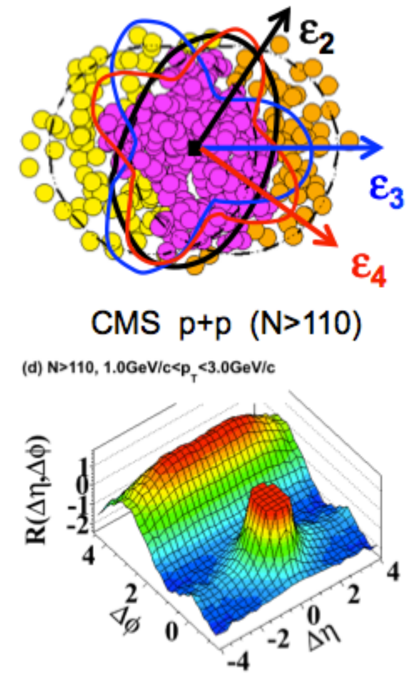
Power spectrum extracted from CMB.
Most power is in l~200 corresponding to small distances.

A 3D-view of partons in the proton?



A.V. Belitsky, D. Muller, NP A711 (2002) 118c

Shape of the matter via final state interactions?



Summary

- We created a Quark Gluon medium that is hot and dense; strongly interacting (hence small mean free path and low viscosity); and very opaque to jets; and hadronize via quark coalesce.
- We are able to quantify some of its properties, e.g. $\langle T \rangle$=220MeV,μ_b=29MeV, η/s= fewx1/4π, qhat~3-13GeV/fm^3.
- The inviscid collective expansion provide a way to probe the initial partonic geometry of the nucleus.

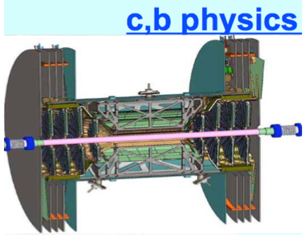
But what is Quark Gluon Plasma?

"The major discoveries in the first ~~five~~ years at RHIC must be followed by a broad, quantitative study of the fundamental properties of the quark gluon plasma …"

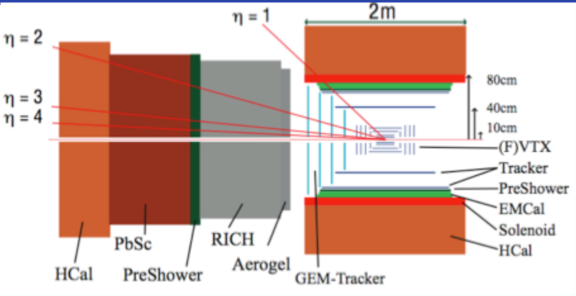
The Frontiers of Nuclear Science A Long Range Plan - 2007

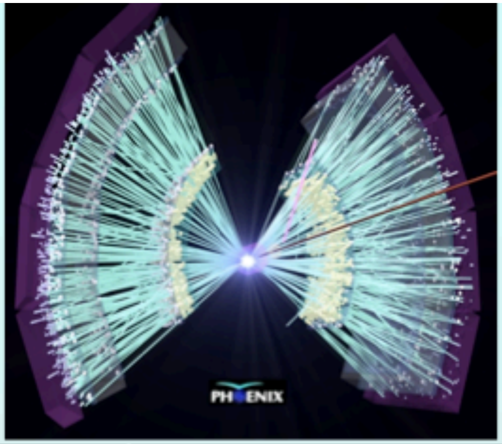
Next Decade of RHIC, WG7S1 E. O'Brien, J. Dunlop

The future: sPHENIX

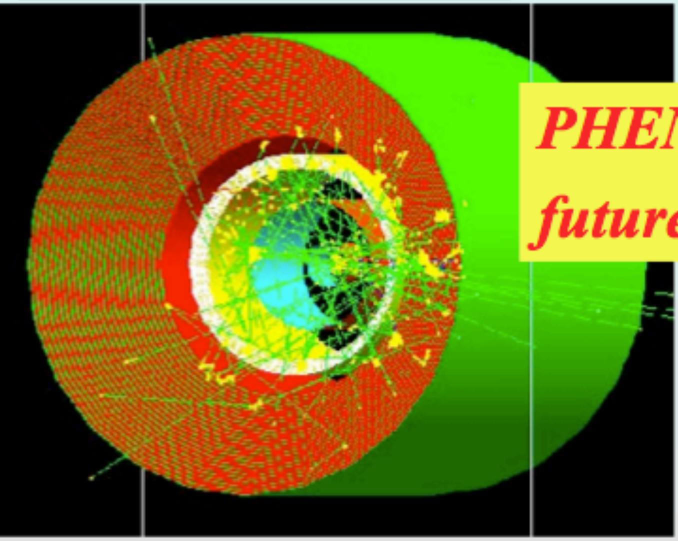


FOCAL:
tracking
calorimeter
1.2<y<2.5
γ_{dir} R_{dAu}
$\pi^0-\pi^0$, $\gamma-\pi^0$
correlation





PHENIX now



PHENIX future

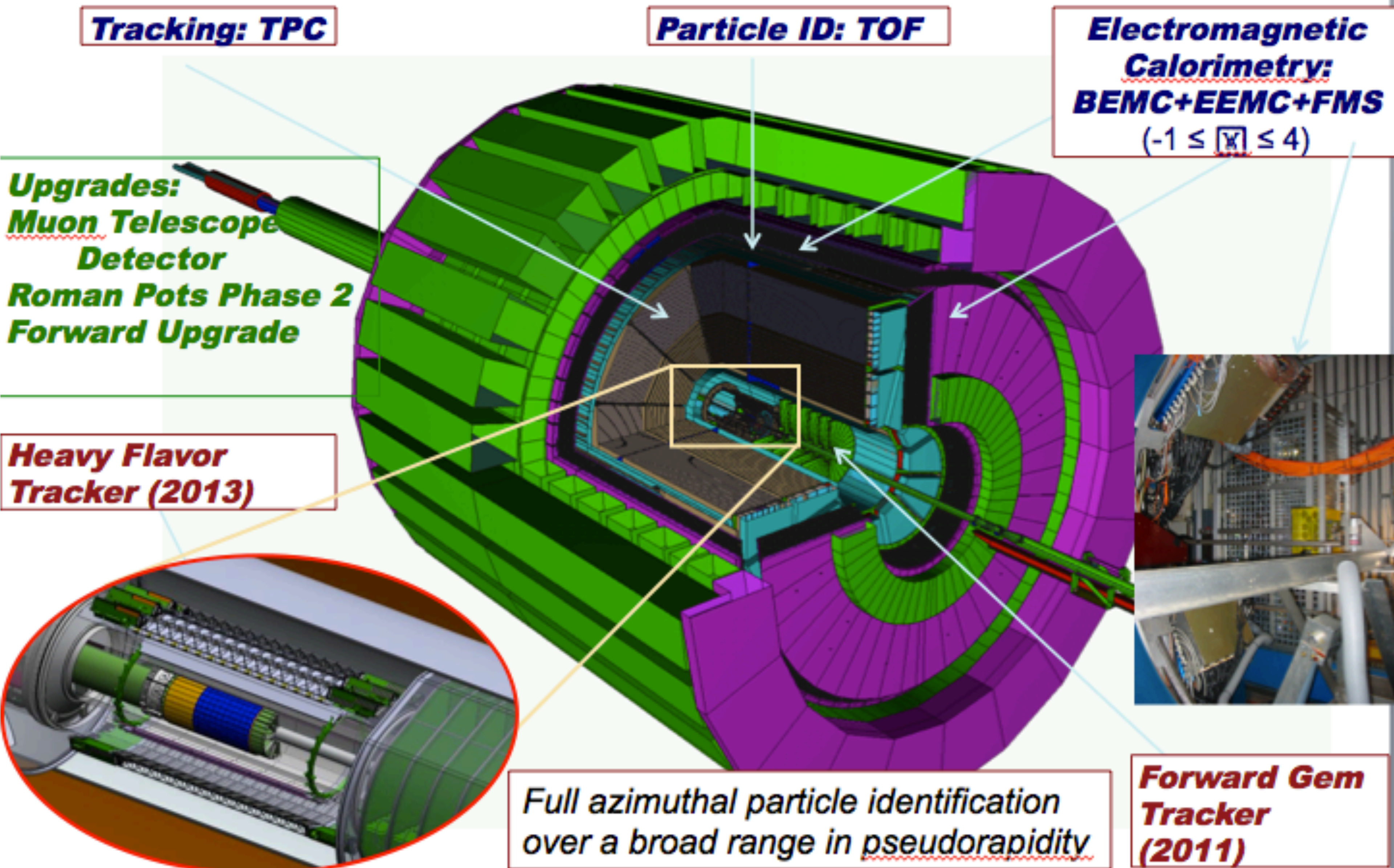
Three phases:

Midterm Physics Plan
Installation of current upgrades- heavy flavor, forward photons

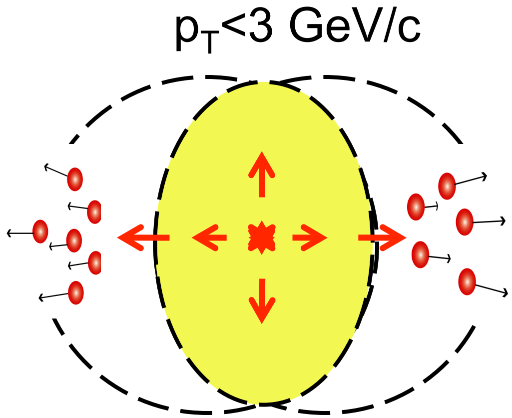
sPHENIX Physics Plan
Major detector configuration change with exciting prospects
A new era in jet physics at RHIC!

SuperQCD Era → RHIC + eRHIC with PHENIX EIC capabilities

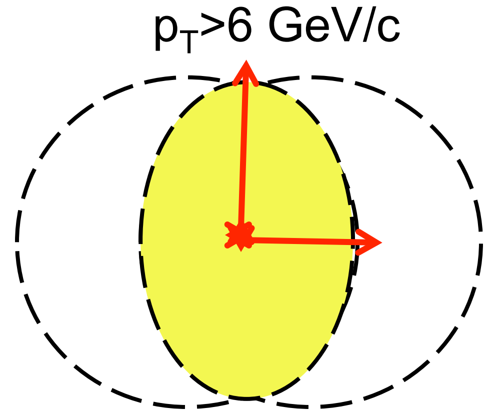
STAR: A Correlation Machine



V_2 measurement for high p_T particles



Low p_T: collective expansion



High p_T: path length dependent quenching

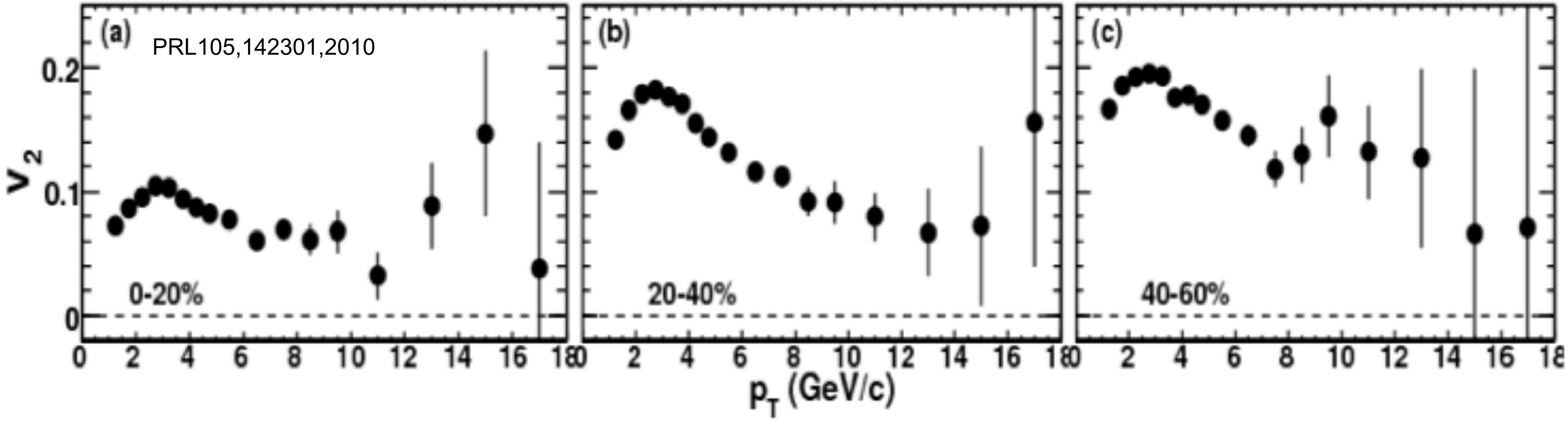
- Anisotropy at low p_T is sensitive to collective flow
- High p_T is more sensitive to the path length dependence of energy loss.

QCD-perturbation theory $\Delta E \sim L^2$

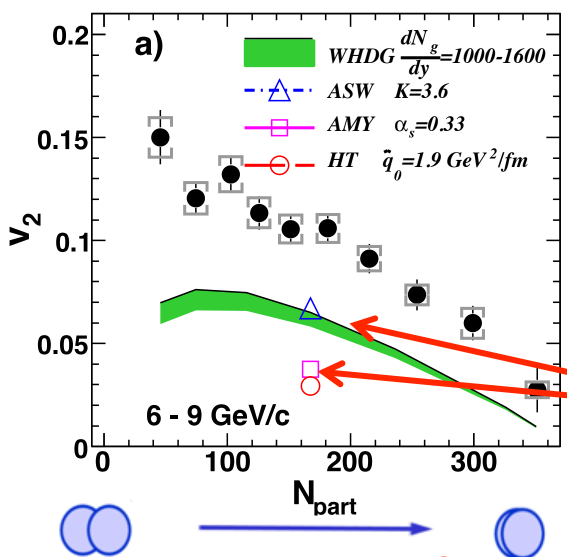
AdS/CFT String theory $\Delta E \sim L^3$

Probing the L dependence of energy loss

- v_2 measurement extended to beyond 10 GeV/c, well into eloss region

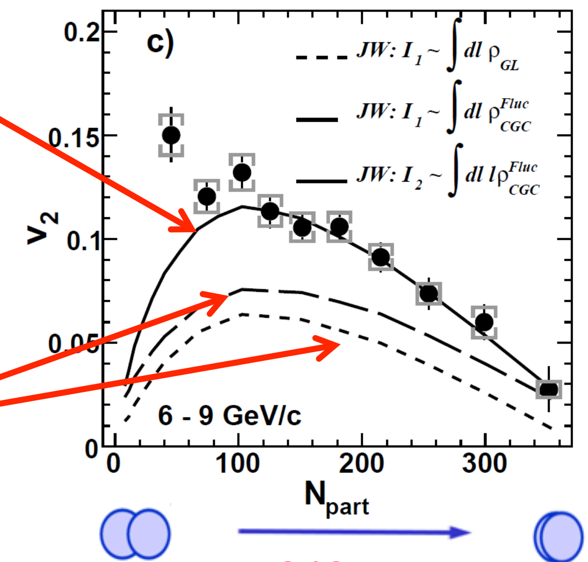


- pQCD models failed to reproduce the magnitude of v_2 up to 10 GeV



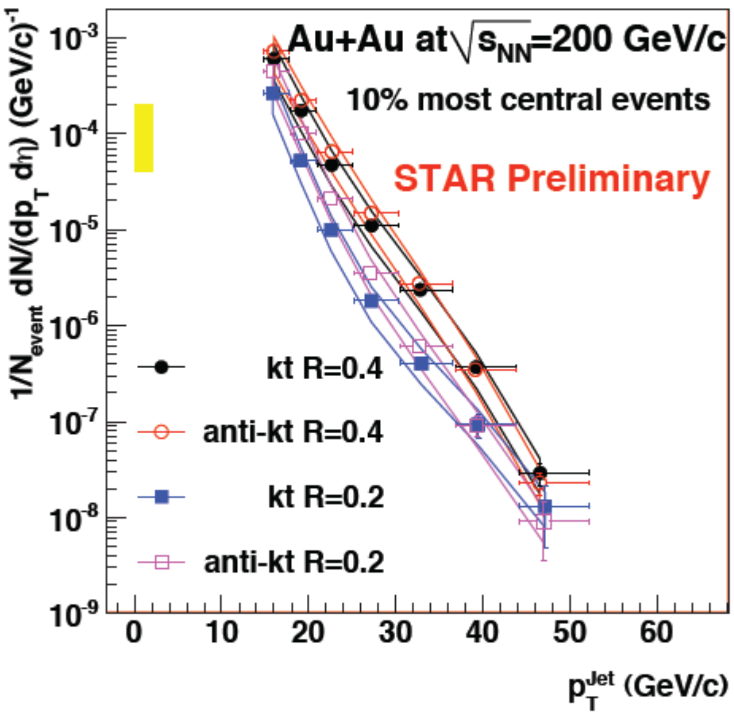
$\Delta E \propto L^3$

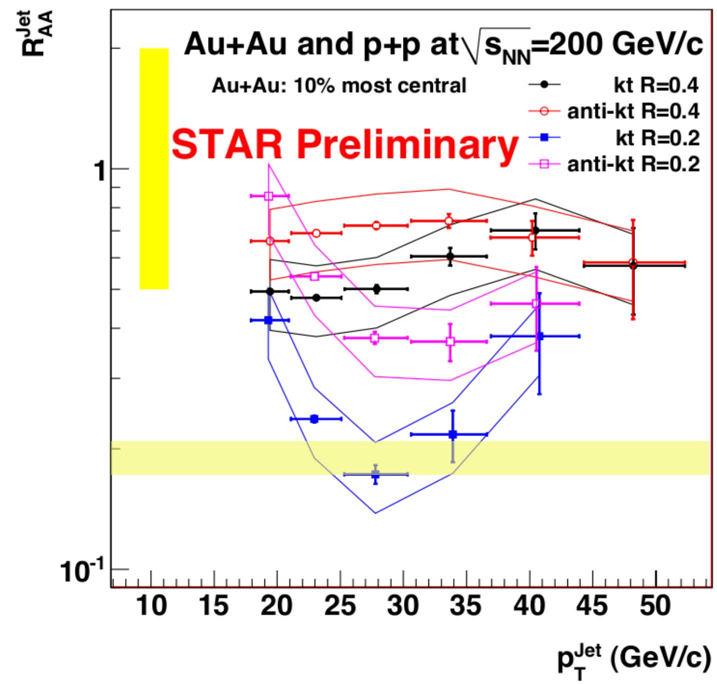
$\Delta E \propto L^2$



Surprisingly, more consistent with AdS/CFT!!

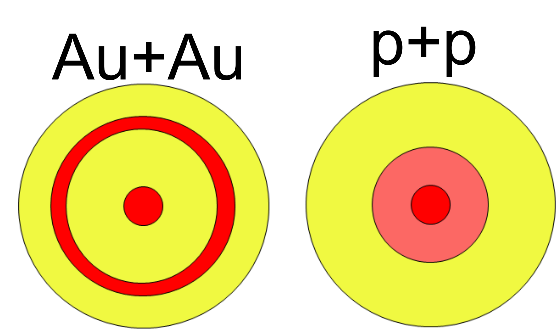
R_{AA}^{Jet}





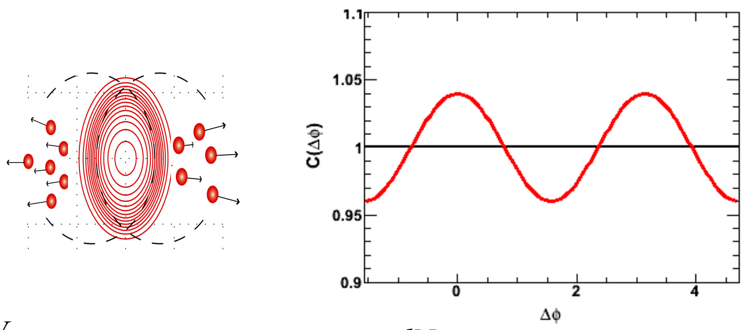
- Smaller jet definition produces more suppression in yield
  - k_T jets smaller than anti-k_T
- Relation between R_{AA}^{Jet} and R_{AA} is non-trivial.
  - R_{AA}^{Jet} depends on jet shapes in both AA and pp.

e.g. same leading hadron as pp, but ring like soft fragments➔ $R_{AA}^{Jet} < R_{AA}$



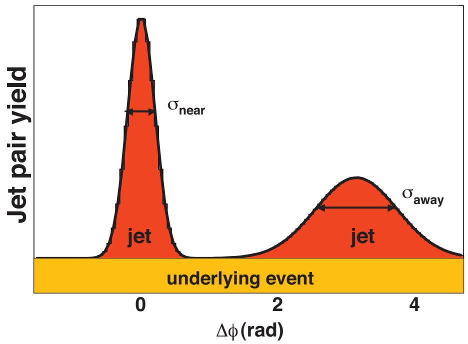
Disentangling jet and flow for low p_T correlation

Flow correlation

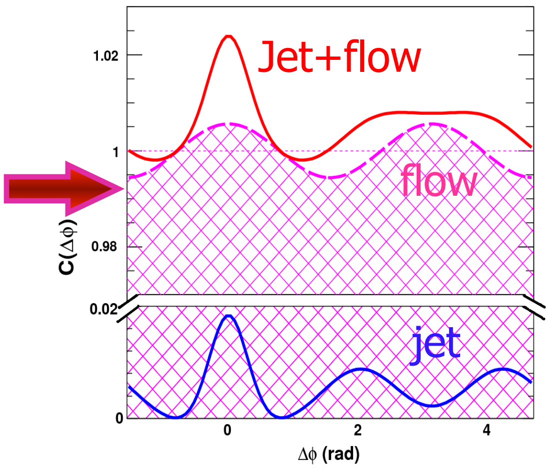


$$\frac{dN}{d\phi} \propto 1 + 2V_2 \cos 2\left(\phi - \Psi_{RP,2}\right) \qquad \frac{dN}{d\Delta\phi} \propto 1 + 2V_2^a V_2^b \cos\left(2\Delta\phi\right)$$

Jet correlation



Flow + modified jet?

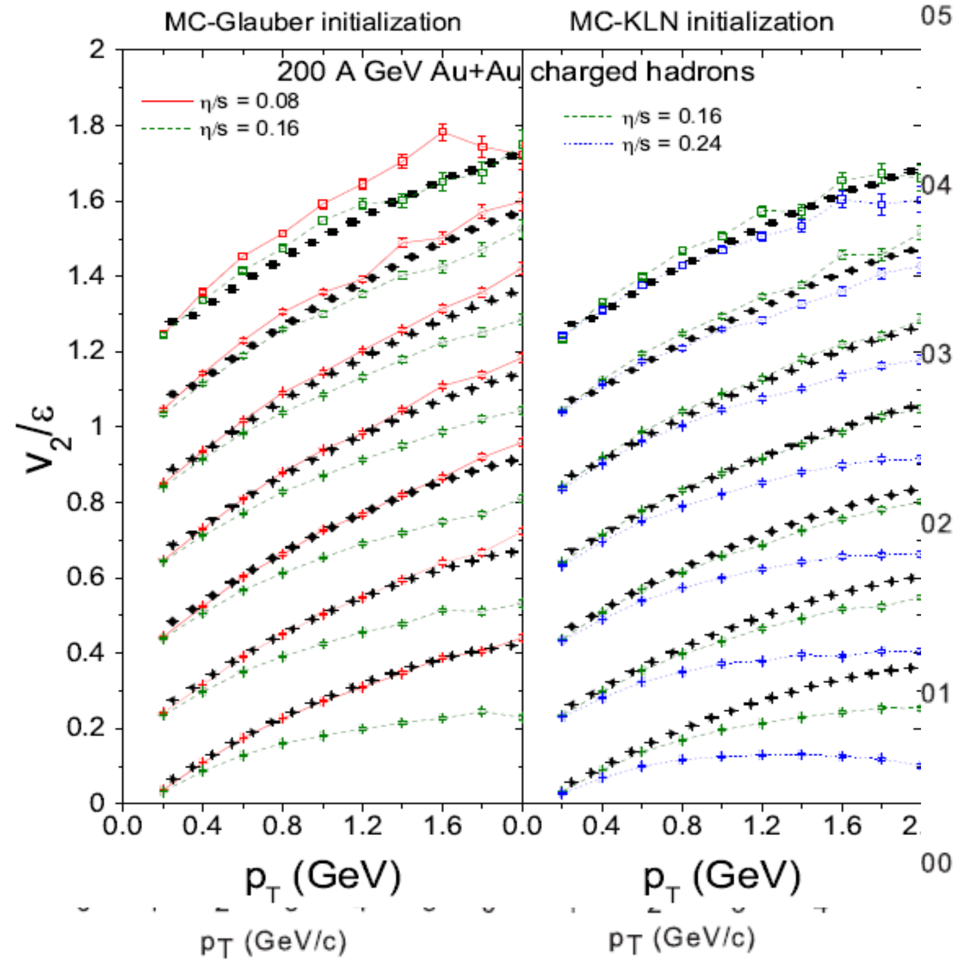


- Global correlations with impact parameter lead to self-correlations among particles. But flow peak coincides with jet pairs
- 2-p correlation is separated into jet and elliptic flow components – up to late 2009 nucl-ex/0507004 arXiv:0801.4545
- We now know this is insufficient

Improved constraint on η/s

- High precision double differential measurement allow between constraints on η/s.

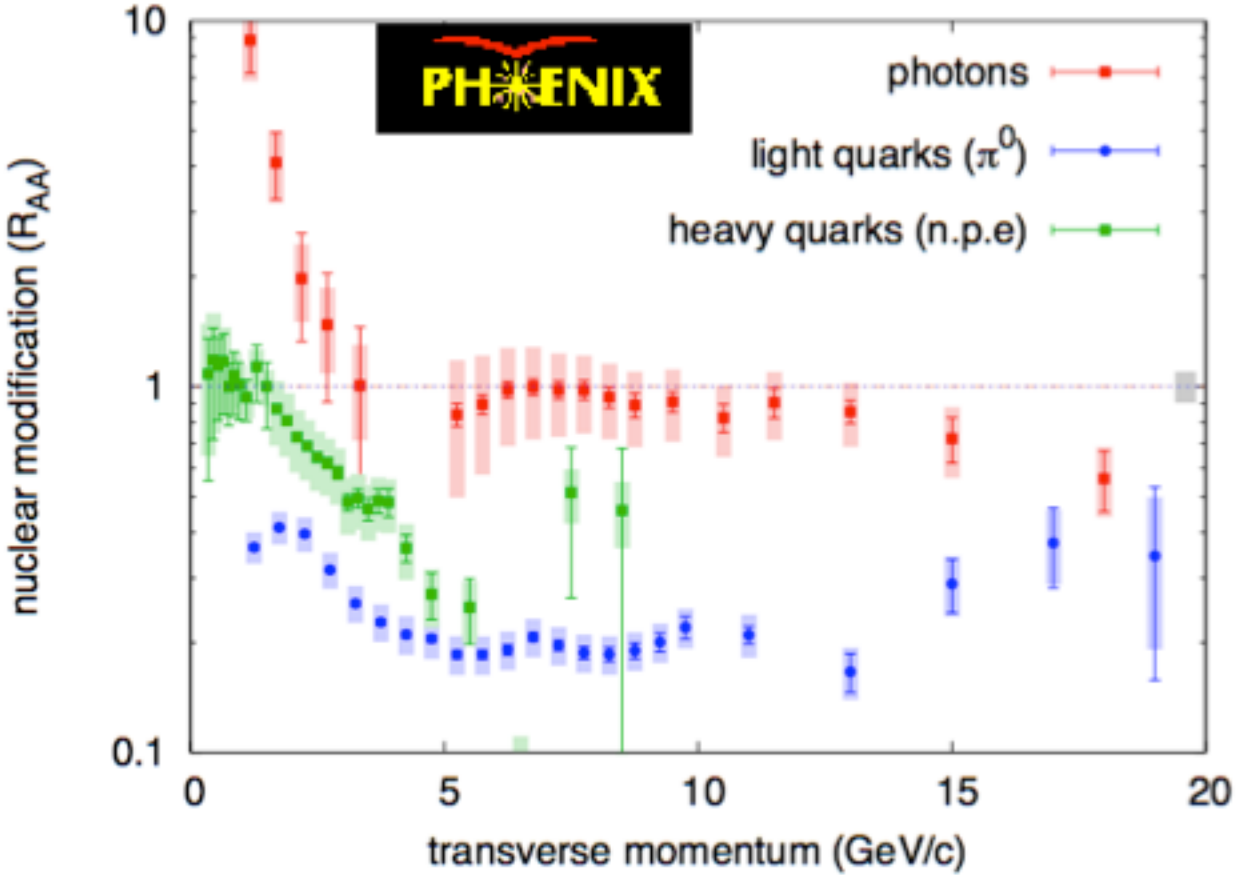
PRL105.2010



H Song, arXiv:1101.4638

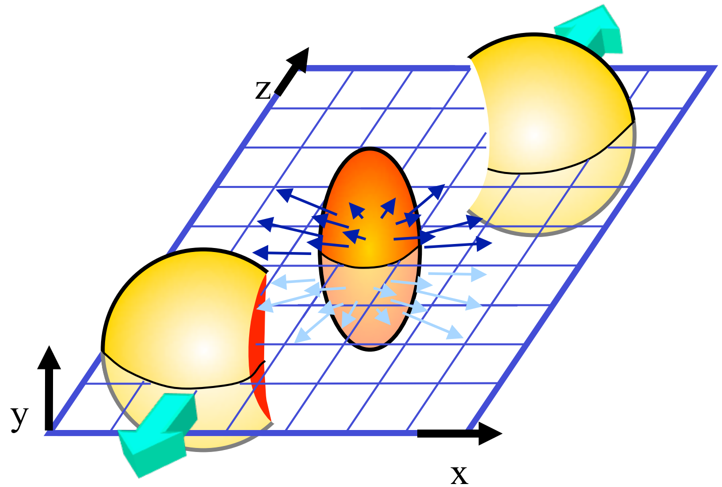
$$\frac{\eta}{s} = 1 - 2.5 \times \frac{1}{4\pi}\frac{\hbar}{k_{\mathrm{B}}}$$

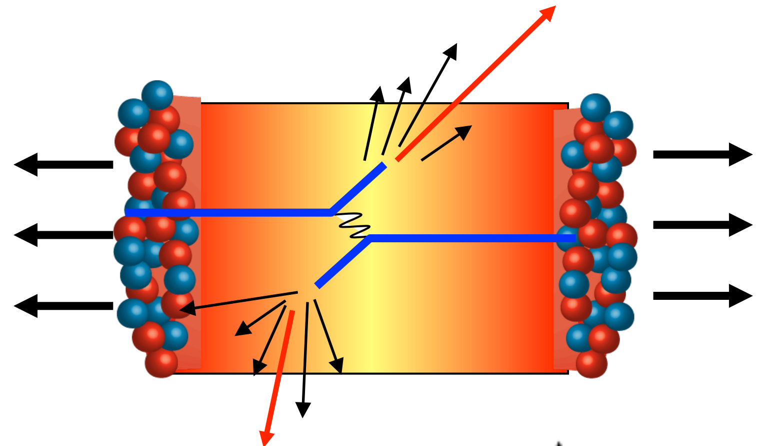
- d



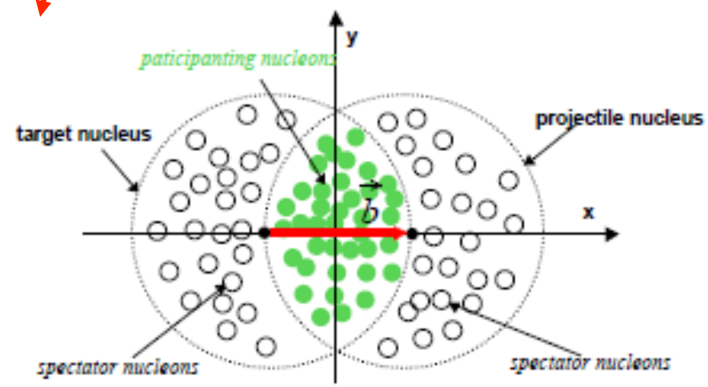
PHENIX
photons
light quarks (π^0)
heavy quarks (n.p.e)
nuclear modification (R_{AA})
transverse momentum (GeV/c)
10
1
0.1
0
5
10
15
20

Geometry of the bulk matter

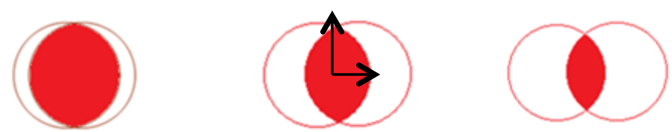




- Observables controlled by the geometry
- Some common terminologies
  - Participants, spectators, number of collisions.



  - Centrality: the amount overlap, percentile of cross-section or number of participants



  - Reaction plane: orientation of the fireball, defined by beam & b direction.